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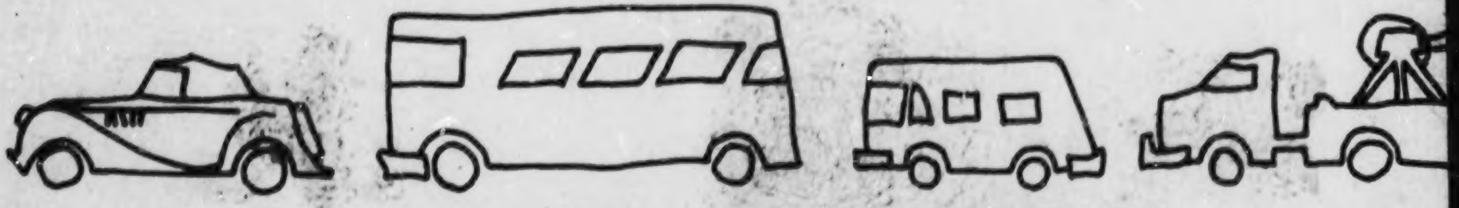
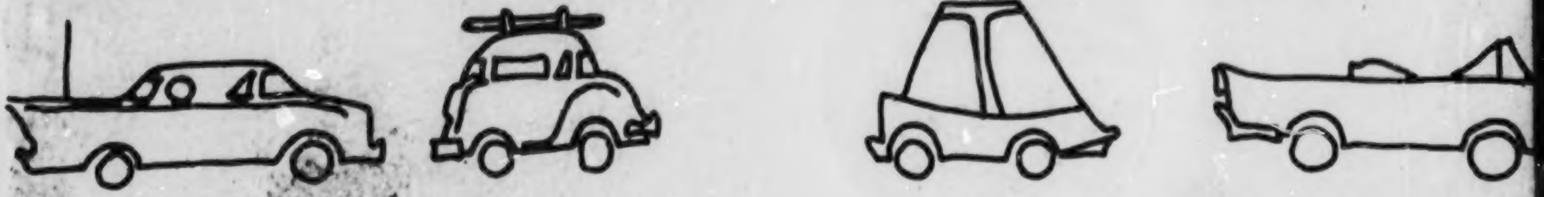
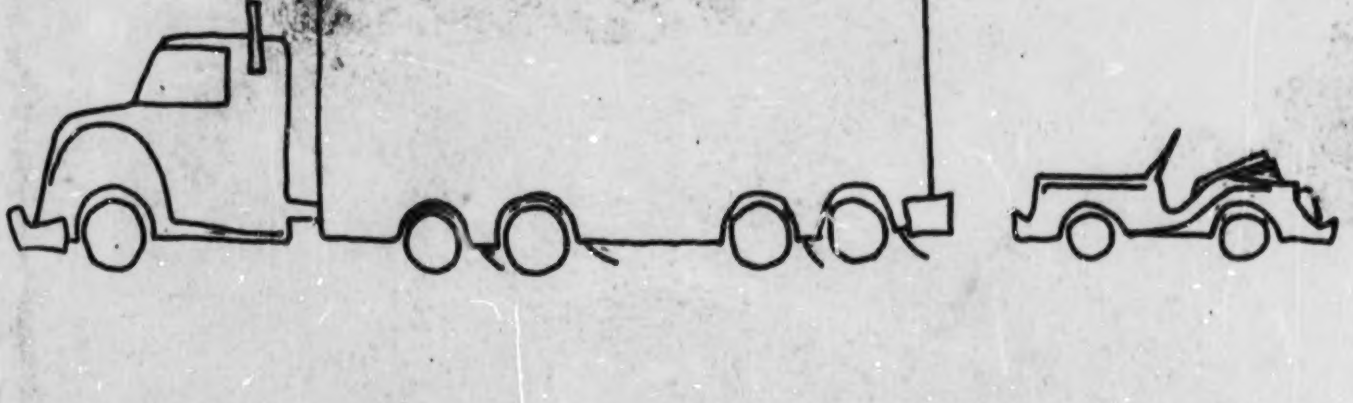
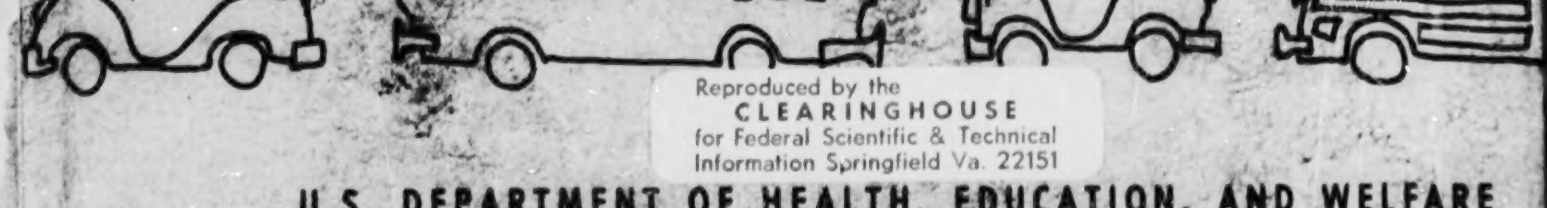


POWER SYSTEMS FOR ELECTRIC VEHICLES







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U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service

PB 177 706

POWER SYSTEMS FOR ELECTRIC VEHICLES

National Center for Air Pollution Control
Cincinnati, Ohio

1967

POWER SYSTEMS FOR ELECTRIC VEHICLES

A Symposium sponsored by
The U. S. Department of Health, Education, and Welfare
Columbia University
and
Polytechnic Institute of Brooklyn

April 6-8, 1967

Chairman
H. B. Linford, Columbia University

Co-Chairmen
H. P. Gregor, Polytechnic Institute of Brooklyn
B. J. Steigerwald, Public Health Service

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Bureau of Disease Prevention and Environmental Control
National Center for Air Pollution Control
Cincinnati, Ohio

1967

The ENVIRONMENTAL HEALTH SERIES of reports was established to report the results of scientific and engineering studies of man's environment: the community, whether urban, suburban, or rural, where he lives, works, and relaxes; the air, water, and earth he uses and re-uses; and the wastes he produces and must dispose of in a way that preserves these natural resources. This SERIES of reports provides for professional users a central source of information on the intramural research activities of the Centers in the Bureau of Disease Prevention and Environmental Control, and on their cooperative activities with state and local agencies, research institutions, and industrial organizations. The general subject area of each report is indicated by the letters that appear in the publication number; the indicators are

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Public Health Service Publication No. 999-AP-37

PREFACE

The National Center for Air Pollution Control, the Polytechnic Institute of Brooklyn, and Columbia University sponsored a symposium on Power Systems for Electric Vehicles at Columbia University April 6, 7, and 8, 1967. The purpose of the symposium was to provide a coordinated review of current research activities related to power systems for electric vehicles. The meetings were designed both to define the present status of our knowledge and to stimulate research.

As chairmen of the symposium, we want to thank Dr. John H. Ludwig and Mr. Anthony H. Sweet of the Public Health Service for their cooperation and assistance; Mrs. Anne Cassel, of Dr. Ludwig's staff, provided editorial services in preparation of these proceedings. Finally, the devotion of Miss Donna McManus, Secretary of the Symposium, to the never-ending details is greatly appreciated.

Henry B. Linford
Harry P. Gregor
Bernard J. Steigerwald

New York
Washington, D. C.
1967

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POWER SYSTEMS FOR ELECTRIC VEHICLES

We have allowed ourselves to so contaminate the air space above most of our major cities as to endanger the health of the inhabitants. Although the total contribution of pollutants emanating from internal combustion engines is debatable, we do not have to argue about exact percentages, since there is almost uniform agreement that automobiles are a major contributor.

The U. S. Department of Health, Education, and Welfare, through its National Center for Air Pollution Control, asked us to cooperate with them in arranging to bring together the leaders of the scientific and engineering world and delineate the state of non-polluting power systems existent today. We hope to point out where progress can be made most expeditiously, with the result of reducing the lead time for the commercialization of the electric vehicle.

Henry B. Linford
Columbia University

PROBLEMS IN OUR CITIES: polluted air, tangled transit; why we think about electric vehicles.

The air pollution problem is more complex than is generally recognized. It varies in form and intensity throughout the country, but the gasoline automobile is a principal contributor to the total pollution. This country now has over 80,000,000 automotive vehicles; no simple mechanism can be suggested to attack a problem of this magnitude.

The automotive industry must of course undertake the introduction of improved automotive engine designs and emission control devices. Our committee is receiving excellent cooperation from the automobile companies and the oil, chemical, and other industrial groups. I am confident that the emission characteristics of future automobiles will be substantially improved.*

---

* Mr. Morse is a member of the Technical Advisory Board of the U. S. Department of Commerce. Currently he is chairman of the study panel appointed by the Secretary of Commerce to deal with the automotive air pollution problem.

The public must clearly recognize its responsibility and assume the necessary costs associated with our country's desire to improve the environment in which we live. The Federal government must develop early and realistic short- and long-term goals and standards, both for quality of our air and for the transportation systems themselves.

In retrospect it appears that knowledge and technology available several years ago were adequate to reduce harmful emissions from the gasoline engine substantially, but we have only recently initiated appropriate action at the national level. Because of the 80,000,000 automotive vehicles now in use, the introduction of new and advanced propulsion devices can at best reduce air pollution to a limited extent in the next decade. It is a sad commentary indeed that the very industrial society that is supposed to improve standards of living has in fact made many of our cities uninhabitable relative to the quality of air that was known 50 years ago.

New types of automotive vehicles must be developed that will operate without generating harmful emissions. Our panel studies are specifically directed toward the identification of new types of motive power that are technically and economically feasible and to which the scientific and industrial capabilities of this country can be most profitably employed. The immediate needs of certain areas such as Los Angeles and New York City and future requirements of our growing urban society dictate that government and industry implement a more effective national program than has been evident in the past decade.

Richard S. Morse
Massachusetts Institute
of Technology

AN EXAMINATION OF ALTERNATIVES TO THE GASOLINE AUTOMOBILE

Austin N. Heller

Commissioner, Department of Air Pollution Control
New York, N. Y.

Right here in New York City, because of the convenience and transportation flexibility of the private automobile, New York automotive vehicles consume a billion gallons of gasoline each 12 months. Because of the less than perfect efficiency of the internal combustion engine, about 70 million gallons of this total is discharged into the atmosphere as waste products — unburned hydrocarbons. This wasted gasoline costs New York City motorists about $25,000,000 a year at current prices.

A study of carbon monoxide, hydrocarbons, and oxides of nitrogen emissions has been completed by the New York City Department of Air Pollution Control. I would like to bring to your attention some pertinent data, that will be included in the report of the study.

For the City of New York, we estimate that each day, automobile traffic produces 8,300,000 pounds of carbon monoxide, 1,000,000 pounds of hydrocarbons, and 212,000 pounds of oxides of nitrogen. This information is being correlated with traffic patterns in the City, and the initial evaluation indicates a direct relationship between traffic congestion and emissions. For example, if the average route speed of an autombile is 25 miles per hour, the exhaust gases on the average contain 3 percent carbon monoxide and 1,275 parts per million hydrocarbons.

On another basis of calculation, each car emits 0.17 pound of carbon monoxide each mile it travels at 25 mph. At 10 mph, the rate of emission rises to 0.35 pound of carbon monoxide per mile traveled. This fluctuating rate, crucial to those of us charged with air pollution control in New York City, is due to the increasing traffic congestion resulting from more and more automobiles traveling over a static amount of road space and crowding into a fixed area of land space.

New York City traffic Commissioner Henry Barnes is fond of telling people that the only way to get to the west side of Manhattan is to be born there. Although things are not *that* bad, I would like to emphasize that things are not that bad — *yet*.

Since the beginning of this year, the Department of Air Pollution Control has maintained a five-station carbon monoxide monitoring program in midtown and lower Manhattan, with the samplers operating continuously 24 hours a day, 7 days a week. The first of the stations to go into operation and the one from which the most data have been obtained, is located at 45th Street and Lexington Avenue. A summary of data from this site for the first 2 months showed that during a *normal* workday the hourly carbon monoxide concentration average cannot be expected to fall below 15 ppm from 9:00 a.m. to 7:00 p.m. The New York State ambient air quality objective states that 15 ppm for 8 consecutive hours should not be exceeded more than 15 percent of the time on an annual basis.

On January 24, at the 45th Street location, 15 ppm as an hourly average was exceeded for 11½ consecutive hours, with a high hourly average of 31 ppm. On January 26, 15 ppm was exceeded at 45th Street for 9 hours, with the highest hourly average being 30 ppm. On that same day, and at the same time in the morning, the high hour at Times Square was 21 ppm; at Canal and Church Streets it was 35 ppm; and at Herald Square it was 25 ppm.

The influence of traffic upon carbon monoxide values in Manhattan cannot be doubted. The early morning low, followed by a jump in concentrations during the rush hour is easily discernible. Variations in traffic flow, not only on weekdays but on Sundays as well, can be read from the variations in carbon monoxide readings.

Nationally, 70 million automobiles consume some 600,000 tons of gasoline per day and discharge more than 270,000 tons of carbon monoxide, unburned hydrocarbons, nitrogen oxides, and organic lead.

Where is our automobile population heading? In 1900, this nation's auto population was nil. Today there are more than 70 million private motor cars in the United States, and this figure is expected to rise to 120 million by 1980 — approximately a 70 percent rise. For New York City, this rise will be a *minimum* of 70 percent and I remind you that 1980 is only 13 years away.

From the standpoint of air pollution control, I would like to examine the various types of automobile engines that are either presently in existence or are in a prototype stage.

GASOLINE ENGINES

The potential sources of air pollutants emitted from gasoline engines include blowby gases from the crankcase, exhaust gases, and evaporative losses from the fuel tank and carburetor.

Control of blowby gasses, i.e., the combustion gases that blow past the reciprocating piston, is being approached. These blowby gasses are trapped in the crankcase and piped to the intake manifold where they are returned to the combustion chambers and burned.

Hydrocarbons evaporate from the car's fuel supply system, gas tank, and carburetor into the atmosphere. Experimental systems for control of evaporative losses of hydrocarbons have been designed and appear to be technically feasible.

A national control program is scheduled to begin in late 1967 with the introduction of 1968 models. These vehicles will be equipped to control crankcase emissions completely and to control exhaust emissions to specified levels. Federal regulations for all 1968 models, with engines greater than 140 cubic inches in displacement, restrict carbon monoxide concentrations to 1.5 percent and hydrocarbon concentrations to 275 ppm in the exhaust stream.

Since the vehicles produced during 1967 will pollute the air throughout their 10-year life span, emission controls must relate to air quality standards and projected requirements for populations in the year 1977.

The consideration of air pollution control devices is far from a panacea. A report issued this past December (1966) by the California State Motor Vehicle Board points up the very high deterioration rate of the automotive pollution control device that has been mandatory in that State since 1966.

Tests were conducted on 552 fleet cars with control devices to determine whether they could meet California's criteria for hydrocarbon and carbon monoxide emissions. A direct correlation in the testing indicated that the higher the mileage of the vehicle, the greater the ineffectiveness of the air pollution control device. Of 227 vehicles driven less than 2,000 miles, 37 percent failed to maintain pollution below state limits. Of 15 vehicles driven over 20,000 miles, 13 vehicles, or 87 percent failed. From these data, we can conclude that an extension of this trend indicates that at 50,000 miles all of the vehicles will fail to meet California standards for hydrocarbon and carbon monoxide emissions.

Despite this evidence, "first generation" automotive emission controls are rather impressive accomplishments and are a significant step in controlling air pollution. However, it is interesting to examine these accomplishments in light of the substantial rise made in pollution sources during these past 14 years. Since 1953, the vehicle population has increased 64 percent and gasoline consumption has increased 73 percent.

The importance of figures such as these is that they present a direct challenge to the various professionals to move faster than the expected rise in population and the concomitant rise in the automobile population. Looking back, we would have had to reduce emissions by at least 70 percent since 1953 just to stand still.

The task that faces planners in air pollution control in relation to the gasoline engine seems to be formidable, but I do believe that it can be mounted.

The problem of technology keeping up with rising population, be it human or automotive, may be new to the engineer and scientist, but it is old hat to to the developmental economist, who long has had to contend with Malthusian equations. Perhaps we might borrow from the economic developer one of the most useful tools at his command — that of developmental capital, or seed money.

If the automotive and gasoline industries who have a stake in finding viable solutions to the problem of automotive pollution control would voluntarily pool 5 percent of their advertising budgets, which would amount to about 12 million dollars based on 1965 data, toward a joint effort at new and better controls, I believe progress would indeed be hastened.

GAS TURBINE

Following World War II, the gas turbine engine became the dominant source of power for the aircraft industry. The gas turbine engine for land-vehicle use had to be much smaller, however.

Such an engine has now been developed by the automotive industry, but fuel consumption is extremely high and must be reduced especially at less than peak load.

The turbine blades must be subjected to the maximum cycle temperatures, thereby necessitating a great amount of excess air to cool the hot gas temperatures.

Another deterrent to widespread utilization of the gas turbine engine in automobiles is the very high cost of needed regenerators or heat exchangers. If ways can be found to raise the maximum cycle temperatures and reduce engine cost, there is no reason why the turbine engine cannot become competitive for automotive use.

The cost of manufacture is likely to remain high for many years, and should the cost go down, there is still the consideration of extensive retooling on the part of the automotive industry to meet any changeover from piston engines.

From a pollution control standpoint, exhaust emissions from gas turbine engines are very low. Tests indicate that emissions of unburned hydrocarbons and carbon monoxide from a turbine-powered vehicle are approximately one-tenth those from a piston-engine-powered vehicle, based on emissions per pound of fuel burned. Unfortunately, emissions of oxides of nitrogen do not compare favorably with those from the present gasoline engine.

Considering the stage of development of turbine-powered vehicles, we should point out that even for heavy trucks, which are considered the most likely outlet for first application of the gas turbine, production is well beyond 1970.

Through our efforts, New York City is to become the test site for the first thorough evaluation of a gas turbine bus. The bus is expected to be delivered before the end of this year and, through the cooperation of the Department of Air Pollution Control and The New York City Transit Authority, will be given its first practical emission and performance tests.

ELECTRIC AUTOMOBILE

Between 1959 and 1961 there was a great flurry of activity when several newly designed versions of the electric automobile were placed on the market.

The various batteries considered for the light trucks and passenger vehicles represented a considerable improvement over those that were tested during the first quarter of this century. Nonetheless, advances in technology have not yet provided a satisfactory battery.

The storage-capacity-to-weight ratios for the relatively inexpensive lead-acid type of battery were too low, limiting the speed and range of the vehicles. The nickel-cadmium and silver-zinc batteries were too expensive.

The production and sales of battery-powered, material-handling transport devices for industrial use have gained great acceptance. Today, more than 100,000 are used inside plants in the United States where air pollution from internal combustion engines is either dangerous or undesirable.

Despite this positive start, electric vehicles for street and highway utilization have not fared well commercially.

After several years of testing on the part of commercial corporations and governmental agencies a few facts have become apparent. We have found that the energy storage capacities of conventional batteries are too limited or too expensive to provide an acceptable energy source for electric passenger cars, or any short-distance electric vehicle.

A substantially superior method of storing electrical energy that will provide much greater storage capacity per unit weight and volume will have to be developed to meet the needs. A great deal of progress needs to be made on electric motors, controllers, and chargers. Further, we have seen that research and development must explore the entire electric automobile, not merely a few individual components.

Significant improvements in the energy density of storage batteries have been made in recent years. Further improvement may prove to be difficult, and there exists doubt that they can meet the requirements of electric vehicles. Because of the physics of the problem, we know that frequent acceleration, gradiant climbing, and high-speed driving place a heavy burden on batteries, reducing the range of the vehicle.

Because of the basic limitations of existing battery systems, a number of companies are conducting research on new systems. Several of these designs show considerable promise, but as yet it is not clear whether or not they would be desirable for electric automobiles. All of these new systems are in the developmental stage, and will require between 5 and 10 years of additional developmental work and testing before they can be shaped into an acceptable energy source for electric vehicles. The most essential component of an electrically powered vehicle is the battery, and it is confronted with serious developmental problems. Consequently, until a battery with suitable characteristics is developed, there is little incentive to attempt development of a practical electrical car.

Until now, most of the road testing for electric vehicles has taken place in converted gasoline-powered cars. These internal combustion cars, stripped of their engines and adapted to operate with rechargeable batteries, are not an ideal medium for testing electric car performance. A specially designed "electric car" should eliminate all components not specifically needed, reduce the weight of other parts, and allocate a much greater share of the weight to the motor, the batteries, and other essential electrical equipment.

Certain steps must be taken if electric powered vehicles should become a reality, and here I am not referring to that old saw about a new market for long extension cords. Nationally, it would require retooling by tens of thousands of small service stations to meet the energy needs of the vehicles and to adapt to the radically different type of engines.

The market potential of an electric car is probably one-third of the automotive market, based on utilization of the car as a second car or one used primarily for short-distance urban driving. I should like to point out that we in air pollution control have a great interest in even one-third reduction of automotive pollution.

The use of the electric car as soon as one becomes feasible would have immediate effects on the carbon monoxide and hydrocarbon emission problems of our major cities. I am particularly interested in the adaptation of the electric car for use as passenger taxicabs. In New York City, taxis account for about 50 percent of all mileage driven, and most of this driving is done in highly congested areas. The introduction of this vehicle would therefore result in a 50 percent reduction of automotive pollution.

FUEL CELLS

The development of fuel cells for energy is now new. Like all inventions, the spirit of the age dictates whether or not the invention is to be used. For example, the telephone was invented in Austria in 1867, but the need for it was not seen until it was invented a second time, in 1876 by Bell. Movable type, was invented by Pi-Cheng in China in 1041, but it remained for Gutenberg to re-invent and utilize movable type in the mid-Fifteenth century before it took hold.

The fuel cell was invented in England in 1839, but it waited for the development of the NASA space program to provide the first practical application. Fuel cells have a number of advantages: high theoretical efficiency, relatively noiseless operation, and most important from my standpoint, they are relatively free of pollution.

Several major manufacturers have built and tested vehicles powered by fuel cells and have demonstrated that fuel cell technology has progressed to a point where a high-output vehicle power plant is technically feasible. As with most good things, though, there are problems that must be conquered. At present, fuel cells have a heavy weight, large volume, and a short lifetime, and they utilize costly components. They depend on a complicated start-up and shutdown procedure, and there are safety problems involving high voltages and electrolytic leaks.

The costs of the fuel cells today are certainly not competitive with the costs of gasoline-powered engines. However, should it ever come to pass, the economics of mass production is expected to result in a sharp reduction in overall cost. The maintenance costs for fuel cells are completely unknown, and very little indeed is known about the longevity and reliability of complete fuel cell systems.

The commercial possibilities for fuel cells being utilized in vehicle propulsion are good. How quickly and how completely they will be realized depends on the speed and ingenuity with which we can overcome major problems that now prevent fuel cells from competing with conventional power plants.

I question whether the public will pay exhorbitant prices for air pollution attachments or pollution-free cars. If we can develop a pollution-free car that is also a better car and can be economically produced so as not to be priced out of its market, this car will be a prototype that can enter mass production immediately.

I encourage the research and development of such cars, but I also ask that you give consideration to the marketing factors as well, for if we cannot sell it to the public, it is all for naught.

It is evident to me, as I imagine it is to you, that it is safe to assume that full-scale application of alternatives to the gasoline-powered automobile are between 5 and 10 years away, depending upon the direction we finally take. What do we in air pollution control do in this interim? It is necessary to take positive action, because to do nothing is not merely to stand still, but to double and triple the problem for the next generation of planners.

I suggest that we concentrate in these next few years on two key programs: alteration of the urban traffic pattern, and an accelerated program to reduce emissions from certain critically important segments of the traffic load — such segments as taxicabs and buses, for example.

To give you just one idea of how altering the traffic pattern can result in a decrease of pollution, I would like to cite some data from the New York City Department of Traffic.

During peak hours of traffic, we know that there is concomitant traffic congestion. Increased traffic congestion means increased carbon monoxide and hydrocarbon emissions.

Several years ago, when Fifth Avenue and Madison Avenue were two-way thoroughfares, the City Department of Traffic calculated that during peak hours of traffic, the average automobile traveled at 3.5 miles an hour. The changeover of these two traffic arteries to one-way streets resulted in an increase to nearly 18 miles per hour.

An increased emphasis on the development of rapid, convenient, and attractive mass transit systems, similar to those now being operated in Japan, may result in a decrease in the anticipated rise of automobile congestion in the metropolitan area, and therefore a reduction in the anticipated rise in automotive pollution.

Similarly, serious study should be given to the possibility of using mini-cabs, because of their lower exhaust volumes; or of using lead-free gasoline for cabs so that they may be re-equipped with catalytic mufflers without fear that the catalyst will be ruined by lead deposits. Catalytic mufflers are presently being tested on 10 new Transit Authority diesel buses.

I take heart from the progress and achievements we report in the following pages. Knowing the problems and having seen limited success, I hope that your inborn scientific inquisitiveness asks you, as do I, for an immediate acceleration into the research and development of battery systems, fuel cells, and gas turbines.

When John Kennedy was President of the United States, I had the good fortune to be associated with the Federal Government. During a meeting that took place at the time, a task force report was submitted to the President on a vital subject. The Chairman paused to direct a question to the Chief Executive: "Mr. President," the Chairman said, "Do you believe in the power of an idea whose time has come?" The President rose and answered, "Indeed I do."

I submit that air pollution control is an idea whose time has come, and the next few years will demonstrate the power of that idea. We in air pollution control cannot wait for the development of the pollution-free car; we must reduce pollution and we must reduce it now.

IMPACT OF ELECTRIC VEHICLES ON URBAN PROBLEMS

Clark Henderson

Stanford Research Institute
Menlo Park, Calif.

BACKGROUND

Electric vehicles have already had a major impact on urban development. Electric rail cars and electric elevators, both introduced in the late 1880s, were the most important factors in urban transportation for at least 40 years. Their influence on the pattern of urban development is clear. For example, central business districts, such as the Chicago Loop, developed rapidly as old six-story buildings were torn down and replaced by taller buildings with elevators. Much of the growth in urban population was accommodated in suburban communities, which developed in radial patterns along the rail lines extending from the central business districts.

The elevator, of course, has continued its important role. Wilfred Owen reports that there are 45,000 elevators in New York City and that the total length of elevator shafts is equal to the total length of subway tracks. In fact, some people ride greater distances in elevators each day than they travel on the ground.*

The electric rail car has not fared as well. Streetcar systems have almost disappeared from U.S. cities. Rail mass transit systems continue to play an important part in some large cities; and a few new systems, such as BART in the San Francisco area, are either being constructed or planned.

Electrically powered trolley buses are attractive because they are quiet and produce no exhaust, but they have never been extensively used because of their need for an overhead power supply and because of the high labor costs associated with their operation. Electric automobiles, which were introduced somewhat later than rail cars and elevators, had a relatively small impact on urban development.

Gasoline-powered automobiles and buses began to dominate urban development in the late 1920s. The influence of the bus has declined, but that of the automobile has increased tremendously through the years. Today the automobile is the most important mode of transportation in almost all urban areas and is certainly the dominant influence in urban development.

---

* See Wilfred Owen, *The Metropolitan Transportation Problem*, Anchor Books edition, 1966.

NEED FOR IMPROVEMENTS

At present, we have many reasons to be discontented with the transportation services available in urban areas and with the systems that are used. Public transportation services are declining even though urban populations are growing, and many people who do not have access to an automobile suffer inconvenience and hardship. Emissions from buses, automobiles, and service stations add greatly to air pollution problems. Automobiles not only create noise and traffic congestion, but they also require unsightly facilities and are costly and unsafe. Automobiles are also charged with encouraging the unattractive pattern of development called "urban sprawl."

A number of different courses can be followed to improve urban transportation services. Continued development of new rail systems and new highways will undoubtedly provide some relief, but we cannot expect these systems, even on a much larger scale, to correct all present deficiencies while meeting growing needs. It has also been suggested that much of the problem might be solved by improving the design of cities: old cities could be reconstructed and new cities could be built with purpose of reducing the need for automobiles and emphasizing pedestrian travel and public transportation.

NEW SYSTEMS

A third approach, which interests me greatly, would be to develop entirely new transportation systems for use in both existing and future cities. The need for new systems has been recognized in many quarters, and considerable research is being sponsored by federal agencies with the hope that new transportation systems can be developed. An especially noteworthy program, sponsored by the Department of Housing and Urban Development, seeks to plan research, development, and demonstration programs for breakthroughs in urban transportation. We at SRI have recently begun one of the research projects in that program.

We have been impressed with the number and variety of transportation concepts that have been put forward in recent years. We have encountered several dozen different suggestions and proposals. However, only a few of the inventors and promoters have actually constructed and demonstrated their systems or even their key components. Apparently, most of the concepts have yet to be fully worked out on paper.

Considerable work must be done before any new urban transportation systems are completely developed and ready for service. We have little doubt that a number of new systems are technically feasible, but it is not yet clear whether they can be made attractive on economic, social, and political grounds. However, if all goes well, a variety of new systems may be in service within 5 to 15 years.

As it happens, most of the new system concepts call for electrical power rather than for internal combustion engines. Consequently, if new systems are developed from current research efforts, we may enter a second "golden era" of electric vehicles.

Let us consider several of these electric vehicles and some of their possible effects on urban problems.

LARGE ELECTRIC VEHICLES

First, assume that it is possible to replace conventional automobiles, trucks, and buses with battery-powered vehicles capable of providing the same services at the same costs. It seems likely that the most important result of this change would be the elimination of air pollution caused by internal combustion engines and fuel evaporation. This gain might be partially offset by the emissions from electrical power-generating plants, but that problem can be avoided by locating steam plants outside urban areas or by using nuclear power.

Electric vehicles may also be somewhat quieter than conventional vehicles because engine noises will be reduced; however, other disadvantages of the automobile will not necessarily be overcome. Large electric vehicles will still cause congestion; they will continue to be involved in accidents; and they will use unsightly roads, bridges, parking lots, and other facilities.

The function and characteristics of service stations might change. Batteries would ordinarily be recharged at home, and visits to local service stations would therefore be less frequent. However, when batteries had to be charged at a service station, the traveler would be delayed long enough that he might want to use the time for a meal, entertainment or shopping. Thus, service stations could become less numerous, but they might compensate by offering more services and they might be located according to new criteria.

The use of thousands of large-capacity battery chargers in residential districts might require additional distribution capacity in excess of the off-peak capacity that is already available during the night. If so, these requirements may help to accelerate programs to replace unsightly overhead distribution lines with underground facilities.

The use of battery-powered vehicles might tend to encourage the use of tunnels, underground garages and stations, and other enclosed spaces where conventional vehicles cause ventilation problems.

One can also visualize reasonably simple schemes for low-speed movements of empty vehicles. Thus, the adoption of large electric vehicles would probably encourage the development of automatic or remotely controlled parking facilities in central business districts and at other congested areas, such as airports.

These advantages — except for reduced air pollution — do not appear to be compelling. Consequently, if we want car owners to replace conventional vehicles with battery-powered vehicles voluntarily, the new vehicles should be attractive in terms of improved service to the owner and lower costs. It may be many years before such vehicles are available.

SMALL ELECTRIC CARS

In the meantime, there are other near-term possibilities for electric automobiles. One of these is to find new ways to use the low-performance vehicles that can be produced now. I am thinking of vehicles with speed and range characteristics more like golf carts than like automobiles. I am also thinking of their use in low-density residential areas where public transportation is now almost nonexistent. Vehicles of this kind could be used to carry commuters to and from their stations and for other services entailing less than, say, 3 to 5 miles of travel.

The small electric cars could be privately owned. I'm told that several thousand such vehicles are in use today in Long Beach, California, primarily by elderly people. It may be more desirable for a public agency or corporation to furnish vehicles as a public service to an entire community. If this were done, the agency would own, maintain, and service the vehicles; collect fares or rentals; and attend to the storage and redistribution of idle vehicles.

Systems of this kind have not been developed, so comments about their value are somewhat speculative. It appears, however, that such systems would offer a number of advantages.

Small electric cars would be hired by users on a variety of terms —by the month, by the day, or by the ride. The vehicles would be managed as a common pool rather than on individual assignments, i.e., a commuter would turn in his vehicle each morning and would receive a different one at night. Vehicles would be redistributed and reused to reduce the requirement for cars, to minimize the need for parking facilities, and to make cars readily accessible to all qualified users. Thus, many travelers who do not have regular access to a private automobile could be given prompt and convenient service.

The vehicles would be small and highly standardized, and therefore would probably be less expensive than conventional automobiles to purchase and operate. If a high rate of utilization could be achieved, the cost per ride should also be low.

The vehicle would have simple controls and would operate at speeds up to about 25 mph. With additional speed restrictions to, say, 15 mph, the vehicles might also be used safely by children and handicapped people who are not qualified to operate conventional automobiles.

The problems of using small electric cars are currently being investigated. It appears that storage, redistribution, and management present the greatest difficulties. Vehicle design would not be a serious obstacle, but special efforts would be needed to minimize costs.

AUTOMATIC CARS

Now let me turn to another family of electric vehicles that may also have a major impact on urban problems. I will use the term "automatic cars" as the name for a group of systems that call for the operation of relatively small vehicles on exclusive rights-of-way under automatic controls. Examples of such systems are the Westinghouse Transit Expressway and the Stevens-Adamson Carveyor. At least a dozen such systems have been proposed within the last decade.

These systems would have fixed routes and would require exclusive rights-of-way similar to those of modern rail transit systems, but the structures would be much less ponderous. Automatic cars would be much smaller than rail cars and would not, in most cases, operate in trains. Automatic car systems of many kinds can be envisioned. The systems could vary greatly in features such as speed, frequency of service, capacity, network configurations, and stations. One of the simplest automatic car systems was the automated shuttle train considered some years ago for service between Times Square and Grand Central Station. Automatic cars in that service would require low speed, frequent departures, and high capacity. Service would be provided on a single, short route with a station at each end. Another group of systems has been proposed to link airports with central business districts. These systems require high speed, low frequency service, and low capacity. A trunk line would connect the two areas, and two or more stations could be provided at each end of the route. A third group of automatic car systems has been proposed for circulation in central business districts. Such systems would have low speed, frequent service, and high capacity. The network of routes would be complex, with many links and stations. High standards of safety should be attained, and the noise and aesthetic problems of rail systems would be partly avoided.

Automatic car systems would be permanent installations but would provide considerable flexibility in design and planning. Systems could be installed piecemeal; they could be tailored to match varying requirements; and they could evolve to satisfy changing needs.

Such systems have one major limitation — they cannot provide door-to-door service throughout the entire urban complex. The stations would have to be widely separated in residential areas where transportation demands are low and irregular. However, other schemes, such as the small electric cars described above, could be used to supply this service.

DUAL-MODE TRANSPORTATION SYSTEMS

Dual-mode transportation systems represent still another approach to the exploitation of electric vehicles. In recent years, several proposals have been advanced for the development of such systems. The proposals call for small electric vehicles capable of operating on two different types of roadway. In one mode, they operate under the driver's control on city streets with battery power (in the same manner as the small electric cars described above) at about 25 mph. In the second mode, they operate under automatic control on an exclusive right-of-way at about 60 mph, using power drawn from an electrical distribution system in the roadway. The cars would change from one mode to the other at entry and exit ramps in much the same way as automobiles enter and leave freeways.

Again it must be emphasized that these systems have not been developed and cannot be evaluated at present. It appears that the dual-mode system would combine most of the advantages of the small electric cars and the automatic car systems previously described. It would be somewhat less flexible in installation than the automatic systems but would eliminate the need for some of the transfers that passengers would have to make with automatic car systems.

High standards of safety can be provided on the exclusive right-of-way. The roadways for automatic operation would ordinarily be elevated or underground. Roadways would require less land than freeways for equal volumes of traffic. Driverless operation on the exclusive right-of-way would be used to redistribute empty vehicles. Automatic parking and the pooling of vehicles might eliminate most of the parking problems in congested areas.

The dual-mode systems are relatively complex. They will be more difficult to develop than small electric cars and automatic cars and may be more costly as well.

SUMMARY

Large electric vehicles would reduce air pollution but would not necessarily make other contributions to the solution of urban problems.

Small electric cars suitable for use in low-density traffic areas could provide one essential stage of an area-wide public transportation service, and automatic car systems could extend the public service throughout the urban area. Technically, these two systems appear to have the potential for improving transportation services to most of the urban population within a relatively short time.

Dual-mode systems combine most of the advantages of the small car systems and automatic car systems but, because of their complexity, may not be available for many years and may be more costly than the other two alternatives.

Economic, social, and political questions have not yet been resolved for any of these advanced systems.

IMPACT OF ELECTRIC POWER SYSTEMS ON URBAN TRAFFIC FLOW, CONTROL, AND FACILITIES

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The transition to electric propulsion for automobiles is viewed primarily as a means to achieve significant reductions in air pollution and other urban irritants. Though these environmental considerations are paramount, some attention should be given to the perhaps less dramatic effects on the transportation system itself. It will be argued here that these are fairly complicated and that some are not altogether beneficial.

AUTOMOTIVE TRANSPORT TODAY

The vehicles used include trucks for local delivery and for longer trips, taxis and buses for transit, and private cars for commuting, shopping, personal travel, and business. All vehicles have a range of 200 to 300 miles between quick refuelings. However, they differ significantly in performance. The normal full-size American car can accelerate from 0 to 60 mph in less than 15 seconds, and from 30 to 50 mph in about 5 seconds. It can climb a 5 percent grade (about the steepest experienced often on streets designed for heavy traffic) at a speed greater than any present or contemplated speed limit. In contrast, a Volkswagen accelerates from 0 to 60 mph in about 27 seconds, from 30 to 50 mph in 9 seconds. Its top speed on a 5 percent grade is about 55 mph. A heavily laden trailer truck may take more than 100 seconds to accelerate from 0 to 60 mph, and may be unable to go at more than 10 to 15 mph on a 5 percent grade.

Such a wide disparity in performance is harmful to traffic flow capacity and to safety. Capacity is lowered by vehicles that cannot maintain optimum flow speeds. For example, in the Lincoln and Holland Tunnels under the Hudson River, the peak flows occur at about 20 miles per hour. Some trucks cannot maintain this speed on the upgrades and so effect a serious reduction in the number of vehicles these tunnels can serve.

Safety is affected adversely when vehicles of widely different acceleration capabilities are fairly closely spaced at high speed on expressways. These vehicles with low maximum acceleration are forced to oscillate through a relatively dangerous wide range of velocities if they consistently attempt to achieve and maintain "optimally close" headways in a stream where the majority of vehicles are very powerful performers (Helly, 1959). Further, the underpowered vehicles face difficulties in merging with high-speed expressway traffic. It may be argued that safety considerations for high-speed roads are not important in congested urban centers where average effective speeds may be below 10 miles per hour. However, one must remain aware of the fact that today a very high proportion of urban trips take place *partially* on sections of expressways with free flow and speeds of 50 mph or more.

Because of the wide range in size and performance of present vehicles, our road system is generally designed in a very generous manner to provide for everyone. Lanes are wide, and where high speeds are possible and legal, every effort is made to bank curves for such speeds and to provide long acceleration lanes for merging by relatively low-powered vehicles. In signalized grids, the timing of light cycles is geared to the capabilities of all but the most sluggish participants.

There is one important property of present day automotive traffic that is present for every type of vehicle and on every road or street. That is the very high probability of propulsion failure. A typical vehicle may experience about one unexpected stoppage per 10,000-mile-year as a result of running out of fuel, mechanical malfunction, or tire failure. This may not appear to be very large until one considers that a three-lane flow on a 5-mile-long section of expressway produces about 25,000 vehicle-miles in a 1-hour peak period. This would correspond to an expected average of about 2½ stoppages. Because a high proportion of stoppages occur in the main traffic lanes before the affected vehicles can get off, the effect on flow capacity is disastrous: it is part of our common experience that the typical commuter inches his way past such a bottleneck at least once daily!

To provide succor to the stranded and to refuel all vehicles, the present transport system includes a tremendous network of service stations. In 1963 the United States contained 211,000 of these, employing 730,000 persons including proprietors, with gross annual sales of 17.8 billion dollars. These figures are for service stations only; they do not include dealers or repair garages.

Because range limitations are a leading obstacle to acceptance of electric vehicles at today's stage of development, it would be most desirable to obtain the distribution of daily travel distances for various classes of vehicles. Unfortunately, there is little data at hand. One would suppose—hopefully—that the urban vehicle needs a smaller range than the national average. Unfortunately, the evidence does not support this premise. A Regional Plan Association of New York study showed that 72 percent of Manhattan vehicles travel more than 50 miles per day. This is definitely above the national average, which must be based on about 10,000 miles per vehicle per year. Manhattan, like other city centers, has an unusually high proportion of traffic in the form of high-mileage buses, taxis, and commercial vehicles. Available estimates show that, in New York, the average taxi goes about 100 miles per nominal 8-hour shift (a little over 200 miles per day) and the average bus goes about 100 miles per day.

Direct fuel costs may be very important in the selection of power plants for commercial vehicles. There are at present about 40,000 electric bread and milk trucks for local deliveries in Great Britain. These are used, despite the inconvenience of a 30-mile range and a 20-mph top speed, because they save money in a country where off-peak electric power is especially cheap and where gasoline is taxed much more highly than in the United States.

THE TRANSITIONAL PHASE

The English experience with electric delivery vehicles suggests that the present state of development is marginally sufficient for such vehicles in urban areas. However, a somewhat higher performance will be required for passenger vehicles. In the transitional phase, where electric cars must survive in an environment of high-powered internal combustion competition on expressways as well as on congested city streets, the minimum acceptable performance specifications might be:

1. Acceleration from 30 to 50 mph in 10 seconds. To achieve this, a 3,000-pound vehicle requires about 25 horsepower more than needed to cruise at a steady 50 mph.
2. A top speed of 50 mph on a 5 percent grade. To achieve this, a 3,000-pound vehicle requires about 20 horsepower above that needed to cruise at a steady 50 mph on a level road.
3. A range of 50 to 75 miles.

Though these specifications are offered rather arbitrarily, they represent about the minimum performance for safe operation on expressways, for minimum degradation of flow, and for a reasonably significant fraction of the range demand distribution. They would satisfy many commuters and shoppers. However, unless very rapid recharges or battery exchanges are developed, taxis would necessarily continue to use internal combustion engines.

To summarize, early and relatively primitive electric vehicles would be acceptable for local delivery trucks and to some commuters. These vehicles must offer performances at the lower end of the present day spectrum, or better. Because roads and control systems have generally been designed for present vehicles of all types, such an introduction of electric cars would not raise new problems in traffic management.

THE FULLY ELECTRIFIED ERA

When reasonably priced batteries or fuel cells are developed to a stage matching present automobile capabilities, there should be a fairly rapid and widespread transition to electric propulsion. The transition may well be accelerated by governmental incentives or selective taxation, in view of the environmental advantages to be gained.

From a traffic viewpoint, the advantages of such a transition are:

1. The flow capacity of the street network will be improved. A small improvement may be expected from greater uniformity in vehicle responses to driver inputs. The major gain will come from a significant reduction in unexpected vehicle stoppages that delay heavy traffic. The simple electric power plant, with very few moving parts, is very unlikely to expire unexpectedly. Further, there should be no sudden equivalent to an empty gas tank. A fuel cell or battery at the end of its range will still give some power, enough for a vehicle to remove itself from interference with the traffic stream.
2. Safety will be improved. It will be possible to give all vehicles flexible and smooth performance characteristics within a fairly close range, thus minimizing the buildup of irregularities and shock waves in traffic. Braking, if in part by motor induction, will be simpler and more reliable. There will be less danger of fire and no danger of carbon monoxide poisoning from leaky exhaust systems.
3. External controls, such as automatic roadways, will require less instrumentation than for internal combustion power plants.
4. The cost of underground roadways will be reduced by up to 50 percent because of smaller ventilation requirements.

Some aspects of the transportation system will be largely unaffected by the transition because there will still be old vehicles and because there will still be a wide variation in vehicle size and in driver performance. These aspects include the geometric design, construction, surfacing, lighting, signing, and control of the road network. Parking will be affected only insomuch as there may be reduced requirements for garage ventilation and for fireproofing.

One facet of the transition is likely to raise serious problems. It certainly is most attractive to the motorist to experience fewer mechanical failures and to be able to refuel at night by tapping any electric outlet. The gasoline station operator is not likely to be as favorably impressed. One may anticipate that a general transition to electric power would ultimately force the closing of a great majority of the country's 211,000 service stations. The direct economic and social consequences to these businesses and their employees can be weathered, just as with other major technological dislocations in the past (but one must be prepared for substantial political difficulties and a certain amount of government spending in relief of this declining industry). There is another problem, more important in the long run. The many service stations today get their primary income from fuel sales and from routine maintenance. Yet, from the motorists' viewpoint, the stations' ubiquity and long open hours are at least as important for emergency assistance, for rest rooms, and for communications. If the great majority of service stations were to close, the government would have to assume a major new responsibility for the nation's 3 million miles of roadway. A precedent for government-organized service exists on some toll and interstate roads. Experience with these leads one to suspect that vast improvements would be demanded if such arrangements become more widespread.

A possible amelioration of this problem is to continue to fuel vehicles at service stations by using interchangeable fuel cells and specially designed hoists. There are other advantages to such a system. The problem of the long-distance motorist would be solved completely. A very large proportion of urban cars today are stored on the streets, not in garages. If this were to be the case in the future, these vehicles could readily be fueled with interchangeable cells: it would be most awkward for them to require lengthy overnight curbside access to electric power outlets. Further, if the fuel cells are very expensive and have a useful life longer than that of the typical vehicle, the motorists would find it advantageous to rent rather than own them.

REFERENCE

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TYPES OF POWER SOURCES: *reviews of system developments, including several kinds of hybrids.*

Electric power for automobiles came long before piston engines. The first electrically propelled vehicle on record apparently was that of Davenport, a Vermont blacksmith who constructed an electrically powered car in 1834 and ran it on a short stretch of track. Davidson, a Scotsman living in Aberdeen, built a more sophisticated electrically propelled vehicle in 1837. This was only 44 years after Volta's first primary battery, and but 7 years after the principles of the first electric motor had been demonstrated by Negro at the University of Padua; it is evident that engineers then were as alert as they are today in picking up new ideas and in doing something about them.

Davidson's vehicle used primary batteries of iron and amalgamated zinc plates immersed in sulfuric acid. His motor was crude, with the rotor a wooden cylinder carrying copper-wire-wound iron bars between the poles of two electromagnets, with commutating switches mounted on the axle. Basically, it was the same as traction motors used today. His system developed 2 horsepower and was able to pull a 6-ton coach at 4 mph on wooden rails.

In 1851, a similar, but larger, vehicle was built in the United States by Page. His vehicle developed 16 horsepower and ran at speeds up to 19 mph, but the severe jolting over track joints in short order ruined the Grove primary cells he used.

The rapid development of steam during this period diverted attention from battery-powered vehicles, and not until 1888 did the first real electric "automobile" make its appearance, almost simultaneously in England and in the United States. By 1903, the electric "Torpedo" built by Walter Baker had achieved a speed of 120 mph. The trend though was largely to luxury cars for wealthy old ladies, each automobile complete with velvet upholstery and a cut-glass vase to hold fresh flowers. Over the next 25 years, many versions of electric automobiles were built. But with the great developments in piston engines, including invention of the self starter, the electric car was gradually replaced and few were built after about 1930.

Now, the pendulum swings back. Once more electric automobiles are in the public eye, thanks mainly to the fact that they do not emit air pollutants. Electric automobiles offer other advantages for urban transportation: they can be small for crowded city streets, nearly noiseless for residential areas, and extraordinarily convenient for stop-and-go driving. It is unlikely that electric automobiles will ever compete performance-wise with piston-engined cars, and their range is always likely to be limited to 100 miles or so before recharging or refueling is required. Hence, in the future, electric automobiles seem most likely to move us about within cities, with high-powered, high-speed, massive piston-engined cars still being used between cities and for general-purpose driving.

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HYBRID POWER SYSTEMS FOR VEHICLES

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INTRODUCTION

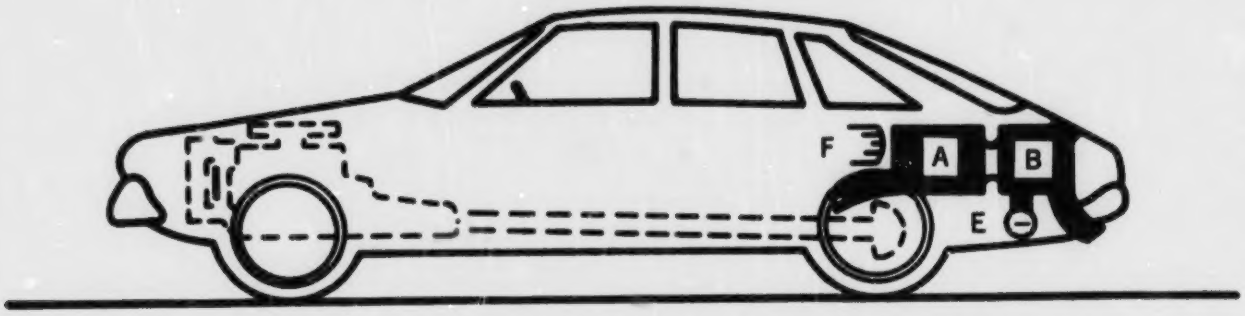
Air pollution has reached catastrophic proportions in many metropolitan areas of the United States. Much of the contamination in the urban air originates from our essential travel by automobile, bus, and truck. Engine exhausts account for over half of the befouling of the atmosphere in New York City and for over three-quarters of the smog plaguing Los Angeles.

It is becoming alarmingly clear that present attempts at controlling and abating the noxious exhausts of the piston engine are too feeble and inadequate. In his message to Congress Jan. 30, 1967, President Johnson said:

> The sheer number of motor vehicles may, within a decade or two, defy the best pollution control methods we can develop. If this proves true, surely we cannot continue to use the type of internal combustion engine now in service. New types of internal combustion engines — or indeed new propulsion systems — may be required.
>
> I recommend an increase of 50 percent in funds to expand our research efforts.

A steep escalation of the war on air pollution must be undertaken soon if urban America is to avoid inundation and suffocation by the effluvium from our transportation. Significant reduction of smog, possibly leading to its elimination, can be envisioned through two distinct approaches to automotive design.

The first approach, illustrated in Figure 1, hypothetically consists of an elaborate array of chemical reactants and scrubbing equipment, occupying most of the space in the trunk compartment of a family car and estimated to cost upward of $500 per vehicle. Pure and breathable air could flow from the final exhaust pipe of this imaginary apparatus. But the accumulated tankage of absorbed products of combustion would require emptying and replenishing every time one pulls into the corner gas station to fill up the empty tank, and probably at a cost comparable to that of the fuel purchased. The logistics and diseconomics of this design approach for pollution abatement by total exhaust suppression appear enormous. The costs and intricacies of full exhaust absorption will undoubtedly cause the American public to resist strongly the mass adoption of this scheme for air purification.



A: UNIT TO CONVERT CO AND HYDROCARBONS TO CO_2 AND H_2O

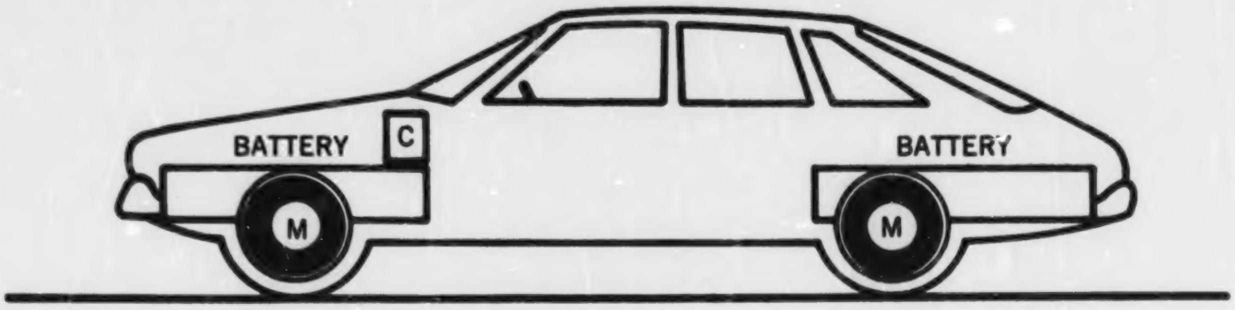
B: AQUEOUS SCRUBBER AND NO_x, CO_2 ABSORBER

E: EMPTYING OUTLET

F: FILLING INLET

Figure 1. Total exhaust controls for piston-engine cars.

The other widely discussed alternative for eliminating automotive air pollution on a national scale is the early and comprehensive substitution of electric-battery-operated automobiles for conventional cars (Hoffman, 1966). But this candidate for cleaning up the urban air also must surmount some formidable obstacles. The concept of phasing out, scrapping, or outlawing a hundred million vehicles powered by internal combustion engines in the United States, and making the transition to a comparable number of electric vehicles in a dozen years or two could easily dismay the hardiest proponent. The appalling obstacles yet to be surmounted in the design of a viable all-electric vehicle are also not to be dismissed too lightly: to this day we lack even small fleets of demonstration prototypes, let alone a single vehicle (as in Figure 2) at reasonable cost, range or performance. Batteries exceeding the critical level of 50 watt-hours per pound are still in the laboratory stage.



C: CONTROLS

M: MOTORS

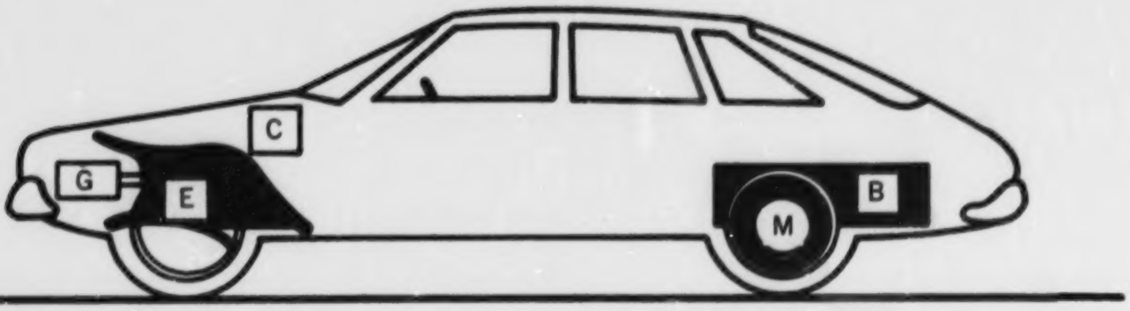
Figure 2. All-electric battery-operated automobile.

Therefore comes our pessimism concerning near-term solutions for enhancing the quality of urban air through radical automotive redesign. In spite of the stated willingness of many to switch immediately to battery-operated cars, or of the certainty that complete exhaust chemoabsorption is technically feasible, neither of these re-engineered vehicles could arrive cheaply enough upon the automotive scene by 1980 to offer a modicum of relief in air pollution levels.

A third possibility for significantly reducing smog is reviewed in this paper: hybrid power systems for passenger cars, buses, and trucks. A hybrid is defined as the enhanced offspring of the union and cross-breeding of the mature form of a male plant species (in this case the internal combustion engine) with the equally mature form of the female of another species (the electric motor/generator). The power package proposed for consideration here is a transitional intermediate between the all-electric and the all-combustive power supply, as shown in Figure 3. The hybrid system consists of an internal combustion engine of rating much reduced from the conventional motor that it supplants driving at its optimal speed a generator. The generated electric power goes to the traction motors (integral with all the wheels) and to a sizeable secondary battery, also connected with the four electric motors. (The suggestion of a traction motor in each wheel of the vehicle is only illustrative. Early designers of hybrids might find it expeditious and simplest to use a single motor driving two wheels, rear and front, through a differential and axle. This would obviate the problems of greatly increased unsprung weight that will eventually arise from installing motors within the wheel rims.) Solid-state controls divert power from both the generator and the battery to the electric motors when the driver's power demand exceeds the capability of the constant-speed engine. When the accelerator pedal demands less power than the internal combustion engine delivers continuously, the controls divert some power to the wheels and some to recharge the battery. If the battery is topped-off, a progressively lesser amount of fuel is metered out to the internal combustion engine.

Replacement of the piston-engine under the hood of today's vehicle by hybrid power sources is the topic of this paper, and its objective is to show the advantages of this substitution in terms of performance, economy, volumetrics, planning, and environment. These advantages have led most Detroit manufacturers to become actively interested in the hybrid concept.

The idea of hybrids occurred to automotive designers a generation ago, though the earliest literature dates back only to the mid-1950's. More recently, Prof. J. L. Shapiro of the California Institute of Technology and Dr. A. L. Stanly of TRW Systems, Inc., studied this concept and brought it vividly to the author's attention in 1966. Prof. Shapiro dubbed it the "gasoline-electric" automobile, whereas Dr. Stanly called it the "quasi-electric" economy car, certainly as appropriate an appellative as our "hybrid" terminology. Dr. G. R.



B: BATTERY
C: CONTROLS
E: INTERNAL COMBUSTION ENGINE
M: TRACTION MOTOR(S)
G: GENERATOR

Figure 3. Schematic of hybrid power systems for cars, trucks, and buses.

Frysinger of the U. S. Army has also aptly used the noun "hybrid" in connection with a power system analogous to the one in this study, but with the internal combustion engine replaced by a non-regenerative hydrocarbon fuel cell (Frysinger, 1966). Not to be outdone by all this activity in the United States, A. P. Zobov in the U.S.S.R. has also engineered a hybrid system by modifying a Moskvich sedan. In England, Jack Brabham, of Grand Prix fame, proposed a battery-powered passenger car with a gasoline engine for charging and occasional peak power.

WHY HYBRID POWER SYSTEMS?

The negative or detractive reasons urging us toward the design of hybrids stem from two sources. First, vehicles operated entirely by battery will not exist in large numbers for dozen of years to come, and even then another decade or two must pass before a dent can be made in the soaring pollution rate. Things look pretty grim for all-electrics until the end of this century. On the other hand, tacking thorough exhaust purifiers onto present-day engines and vehicles is probably an insufferably expensive complexity that might be shunned by most of the motoring public.

The contributive or positive reasons for developing hybrids are threefold: first, they present an early capability for reducing exhaust pollution substantially by use of existing automotive technology; second, hybrids promise a perceptible lowering of operating and fuel costs; third, many beneficial attributes emerge when planning the transition to an all-electric 21st-century America.

The hybrid's exhaust would be proportionately less polluting than its conventional counterpart, for these reasons:

1. In the first-generation hybrid the power output would be about one-half that of the engine it replaces. (It could be even less

in later designs.) Expelled contaminants therefore should also be half of those found in conventional exhaust, if contaminant rate may be assumed proportional to energy-rate as a first approximation.

2. The engine-generator set could be run at fairly constant speed, near the rpm at which minimum specific fuel consumption is achieved and with fixed-setting carburetion. With the patterns of fuel consumption, engine rpm, and time at rpm stipulated in Figure 4, a further pollutant reduction of one-third can be calculated from just running engines at constant optimum speed with non-variable carburetion. For example, Figure 4 shows that an engine dwells only 40 percent of the operating time at its level of least specific consumption, which occurs at 0.3 to 0.6 of maximum rpm.
3. Fixed-speed internal combustion engines allow most easily the incorporation of regenerative heating of inlet air by heat exchangers and recirculation of exhausted gases. The chilled exhaust from the exchanger swept turbulently over large catalytic surfaces, and its partial readmission into the inlet, should lead to an additional reduction of the unburned hydrocarbons and nitric oxide produced earlier in the combustion chamber. This reduction of smog agents, with a well-designed regenerative exchanger, could amount to another one-half.

A well-engineered hybrid power pack could be one-fourth to one-eighth as emissive of smog products as its equivalent piston engine if the three effects just cited are properly utilized and combined. Moreover the heat-exchanger surfaces offer a fine opportunity and base for chemical activation (perhaps in the form of expanded nickel or graphite coatings) and might also be an excellent suppressor of most contaminants except CO_2.*

The second class of beneficial contributions from hybrid power systems is lowered operating costs. Without changing the driver's

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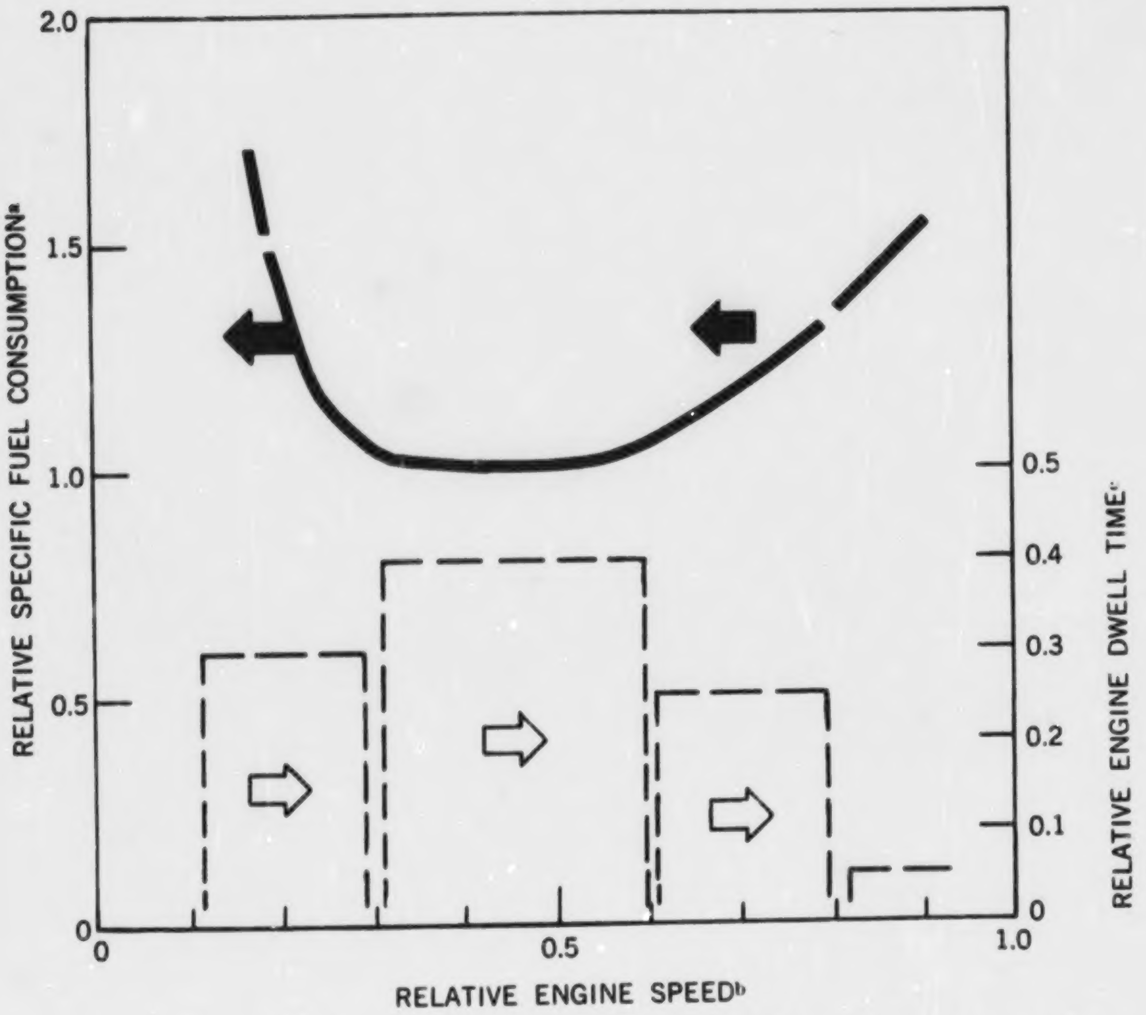
*It is a matter of conjecture how long mankind will consider the massive and rapidly rising effluvium of CO_2 as innocuous. In the first century after the birth of industrial civilization, the CO_2 content of the atmosphere rose imperceptibly by a few percent. Since the turn of this century, it has risen about another 10 percent. It is now increasing at the rate of about 0.5 to 1 percent per annum. At this rate of accumulation, some meteorologists claim the re-radiated heat from earth is decreased noticeably, and by the end of the 21st century the average surface temperature of this planet will register a dozen or so degrees higher than it does now. The polar icecaps will then partially melt, inundating most coastal territories less than 100 feet above sea level.

I do not necessarily hold to such cataclysmic predictions: methods of power generation alternative to combustion will be more widely used; and vast expansion of reforestation, landscaping, and agricultural activities will absorb much of the added CO_2. Fixation of carbon dioxide from exhausts into disposable carbonates or by manipulated photosynthesis will undoubtedly be investigated in the next century, and a workable solution to the suppression of CO_2 emissions might be adopted.



[a] RELATIVE SFC $= \dfrac{\text{SFC AT rpm AND MAXIMUM TORQUE}}{\text{MINIMUM SFC}}$

[b] RELATIVE SPEED $= \dfrac{\text{rpm AT SPEED}}{\text{rpm EQUIVALENT OF 120-mph ROAD SPEED}}$

[c] FRACTION OF ENGINE TIME AT rpm IN AN URBAN TRIP COMPENSATED FOR IDLING TIME AND BRAKING BY ENGINE DRAG

Figure 4. Fuel consumption, engine speed, and time at speed for a 3-year-old engine.

power demand for performance, speed, acceleration, and grade climbing, fuel consumption would be slashed one-third just by the constant-speed operation of the engine (note the patterns in Figure 4). Cheaper and less-refined fuels than those presently required for our variable-speed engines can be fed into fixed-speed engines.

In sum, the fuel costs of hybrids might well be one-half to two-thirds of those of gasoline for conventional engines for equal automotive missions.

Maintenance costs of hybrids also may be perceptibly lower. The on-board diagnostics of constant-speed engines can be readily visualized as a welcome simplification of today's complexities of dashboard gages, warning lights, and other puzzlers. Compressor, gasifier, and power vanes are all on the same shaft as the generator's rotor and at the same rpm. The single rotating part implies much savings in upkeep. Finally the hard-mounted engine-generator unit and the nonmechanical power transmission to the wheels allow for easy powerplant plug-in and replacement, less destructive vibration, and freer interchange of parts.

The last category of advantages for hybrids is less technical and more an ease-of-planning benefit. Hybridizing the power systems of the automobile, the truck, and the bus buys a few decades of breathing time for the more orderly research and development of individual travel means. These few decades of respite could permit a more unhurried evolution of advanced batteries for the all-electric car and a more gradual introduction of the driving populace to electric propulsion. The industrial complex would be less dislocated by the smooth transition of automotive manufacturers from producing all-combustive power components to the mass-production of battery-motor systems. Public utilities would have a more gradual time-table for national rewiring and up-rating of electric distribution to home garages, parking lots, and service stations and for the electrification of our networks of federal highways and limited-access expressways.

The future motorist driving a hybrid vehicle might also avoid for a few more decades the logistics of battery recharging or replacement, and might cling sentimentally for a while to the habit of "filling-her-up-with-gas" every 300 or 400 miles, aside from the cleaner air and the smaller burden on the pocketbook. And the quiet hum of the turbine-generator-motor might yet prove a less offensive sound than the muffled roar of the V8.

Essentially, the hybrids might prove the least traumatic sequential conversion of the internal combustion engine species of vehicles dominating the 20th century into the unavoidably electric mainstays of the 21st. A transition scheme is given in Figure 5.

COMPOSITION OF FIRST-GENERATION HYBRID POWER SYSTEMS FOR AUTOMOBILES

This section examines a specific family of ground-transportation vehicles, the family passenger car, as an example of analogous studies regarding buses and trucks.

I believe that the future electrically propelled vehicle should be a look-alike, act-alike, simple counterpart of the piston-engined

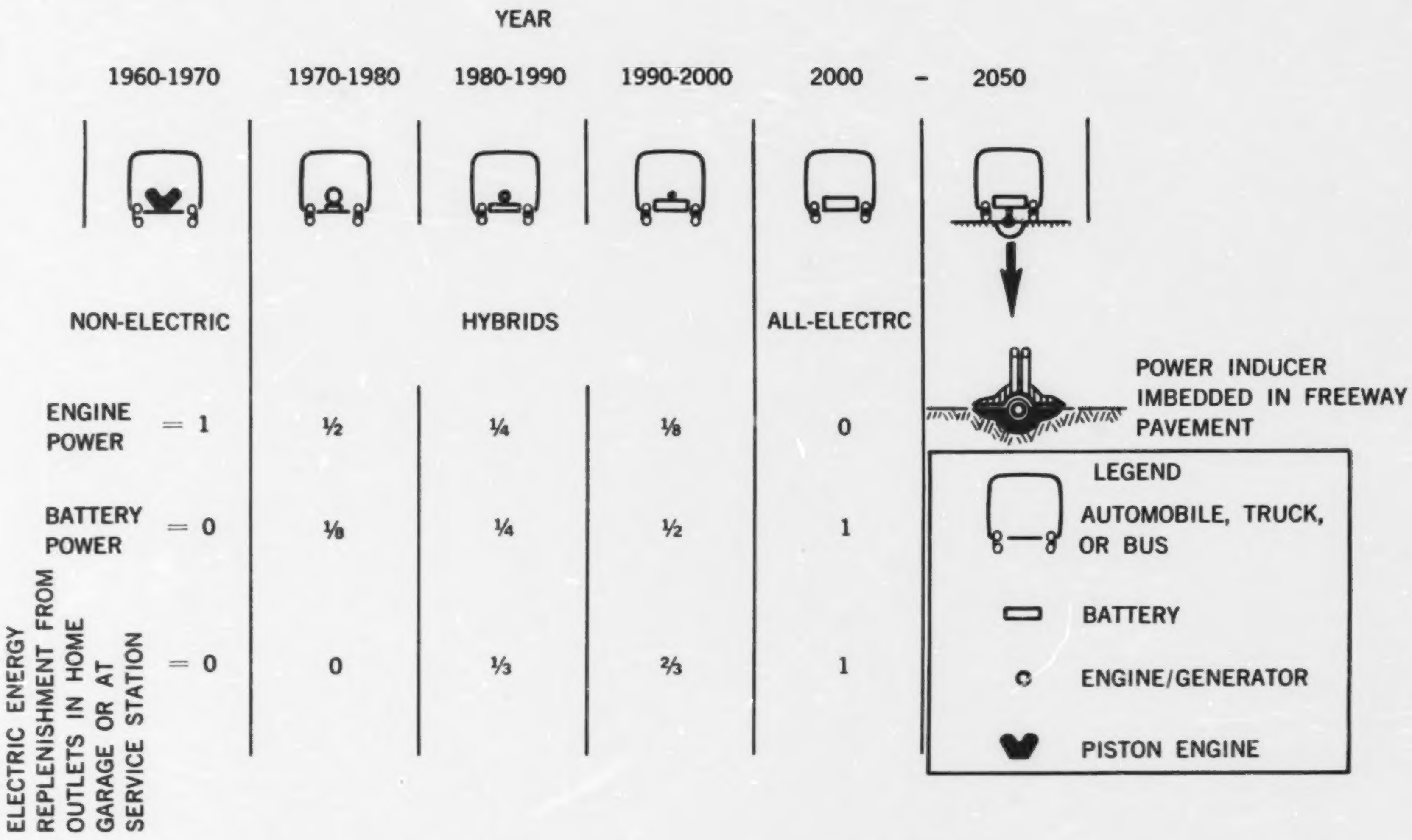

YEAR
1960-1970
1970-1980
1980-1990
1990-2000
2000 - 2050
NON-ELECTRIC
HYBRIDS
ALL-ELECTRC
ENGINE POWER = 1
½
¼
⅛
0
BATTERY POWER = 0
⅛
¼
½
1
ELECTRIC ENERGY REPLENISHMENT FROM OUTLETS IN HOME GARAGE OR AT SERVICE STATION = 0
0
⅓
⅔
1
POWER INDUCER IMBEDDED IN FREEWAY PAVEMENT
LEGEND
AUTOMOBILE, TRUCK, OR BUS
BATTERY
ENGINE/GENERATOR
PISTON ENGINE

Figure 5. Scheme for a transition from non-electric to all-electric vehicles via hybrids.

vehicle with comparable dimensions, performance, and speeds (Hoffman, 1967). Apart from changes under the hood, which tend to be of least concern to most outside observers or to the passenger, I am firmly convinced that hybrid vehicles must conform to the major characteristics of conventional cars of today as regards configuration, power, and spectrum of sizes offered to the public (from small or compact cars up to large luxury automobiles). This premise defines the basic composition and design criteria of the first generation of hybrid-powered automobiles.

The weight compostion of family passenger cars of the late 1960's, ranging in curb weight from 1,500 pounds (a small car) to over 5,000 pounds (a large, luxurious one), is uniform in the proportions of weight of components and in the linearity of subsystem weight with curb weight (Hoffman, 1962). Table 1 lists the ratios of subgrouping weights to overall weight in this decade's automobiles; these ratios are the starting point of this synthesis of hybrid power vehicles.

The next step is elimination or transformation of the car's building blocks that are altered by the substitution of the hybrid powerplant. From the parametric analysis in Table 1 one can forecast that future hybrid vehicles that are identical twins to conventional ones in shape, size, and performance would still call for two-thirds of the vehicle weight to be conventional subsystems, and one-third innovated power systems. In this section I will discuss this innovative third of the vehicle system weight, and its subdivision into engine (denoted in Table 1 by A), generator (B), motors (also amounting to B as a first approximation) and X, the battery weight.

Engine

Having fulfilled the "look-alike" requirement, one must next choose engines to satisfy the "act-alike" requirement. Providing a constant level of power comparable to that available in conventional cars traveling at 50 mph gives three results (see Figure 5, Hoffman, 1967):

1. Accelerative performance from 0 to 30 mph superior to that given by piston-engine cars, even with constant torque provision (rather than power) up to 15 mph.
2. Equivalent performance from standstill to 60 mph, (that is, equal time to accelerate from 0 to 60).
3. Somewhat inferior performance beyond 60 mph, but boostable in hybrids by injection of battery-supplied spurts of power.

The actual power available to the driving wheels of modern passenger cars at 50 mph is shown in Figure 6 for standard and intermediate-performance engine options. An apparent satisfaction with 0.025 to 0.035 horsepower per pound seems to emerge as the urban public's demand level for automotive power, the lower value being for "standard" and the upper for the next-in-line ("intermediate") consumer option of engines.

Table 1. WEIGHT APPORTIONMENT IN CONVENTIONAL AND HYBRID VEHICLES

Component	Conventional vehicle ratio, $\frac{\text{component weight}}{\text{curb weight}}$	Redesign possibilities from substitution of a hybrid powerplant	Hybrid vehicle ratio, $\frac{\text{component weight}}{\text{curb weight}}$
Body	0.33	Elimination of transmission hump; fewer vibration mounts; redistribution of weights	0.32
Trim	0.14	Simplification of dashboard furnishings, controls	0.14
Engine	0.15	See text	A
Starter	0.005	Becomes traction motors in the wheels	B
Transmission	0.040	Eliminated	
Suspensions	0.060	Better balanced front-rear springing; low center of gravity	0.056
Glass	0.032	No alterations	0.032
Wheels	0.025	Incorporation of traction motors	0.030
Tires	0.032	No significant change	0.034
Brakes	0.038	Decelerating function partially taken over by motors	0.020
Steering unit	0.016	More equitable weight distribution	0.016
Rear axle, drive line	0.043	Not needed	
Exhaust, smog system	0.014	Heat recuperator at engine controls exhaust	
Battery	0.012	Size increased to meet high-power peaks	X
Radiator, full	0.014	Eliminated	
Fuel tank, full	0.044	More modestly sized for lowered fuel consumption	0.022
Generator, controls	0.005	Growth into full-power generator on turbine shaft	B

Sum = A+2B+X+0.67 = 1.00

If we assume that the electrochemical conversion efficiency of the hybrid's electric motors and generator is 93 percent, the engine power requirement is then

$$\text{hp} = \frac{(0.03 \pm 0.005)}{0.93^2}\,W$$

and the least horsepower required of the engine is about

$$\text{hp}_{\text{min,I.C.E.}} = 0.029\ W \tag{1}$$

where W is the curb weight of the car in pounds.

The maximum speed of hybrid autos on level grade and without battery augmentation is calculated by equating the actual propulsive power at the wheels

$$\text{hp}_{\text{wheels}} = 0.025\ W \tag{2}$$

with the power needed to overcome aerodynamic drag and tire rolling resistance.

Assume that the tire rolling tractive force (SAE, 1967) of modern tires is

$$0.015\ W,\ \text{lb} \tag{3}$$

and that the aerodynamic drag of a well-streamlined family car is

$$7 \times 10^{-6}\ W\ v^2,\ \text{lb} \tag{4}$$

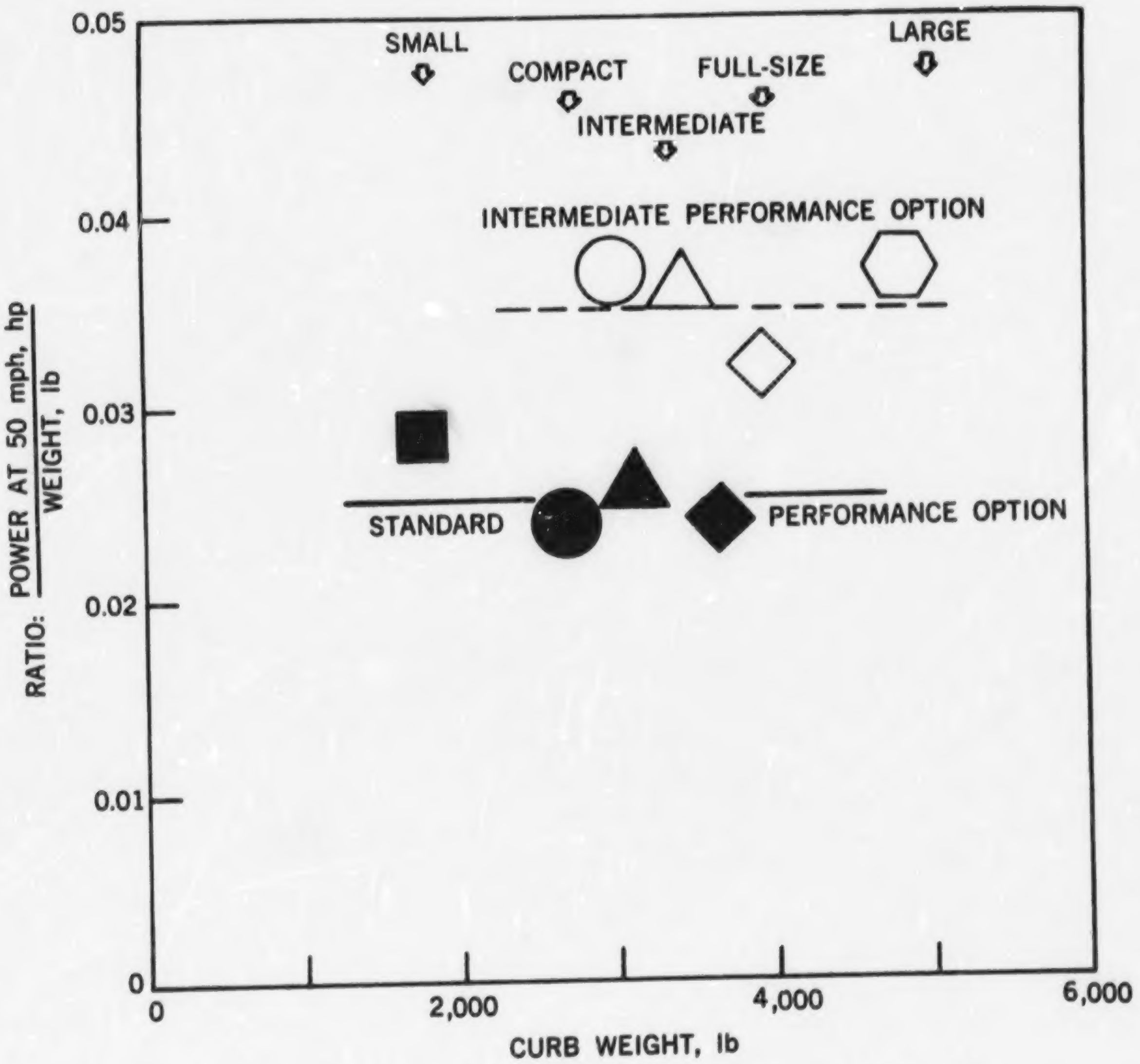


Figure 6. The actual mean power available at the driving wheels of modern passenger cars traveling at 50 mph with standard option and intermediate performance engines.

The total force resisting automotion, i.e., expressions (3) plus (4), when multiplied by the speed, v (mph), and the appropriate conversion factor, is close to the total automotive drag power that is required of the motors. This tractive power requirement (hp) is then

$$0.00267\ (0.015 - 7 \times 10^{-6}\ v^2)\ W\ v \qquad (5)$$

where $$0.00267 = \frac{1.467\ (\text{ft/sec})\ /\text{mph}}{550\ (\text{ft-lb/sec})/\text{hp}}$$

At the top speed of the hybrid not utilizing batteries for power, the horsepower in expression (5) balances the motor-delivered power in (2). Equating expressions (5) and (2) yields the maximum speed, v, to be 103.5 mph. This speed is without resort to battery augmentation, which presumably will be employed mostly for upgrading, during short periods, the poor passing performance of hybrids beyond 60 mph.

The characteristics of some conventional automotive engines that could drive the generator in a hybrid are listed in Table 2. They were derived for a unit of 50- to 100-horsepower output by updating material presented earlier (Table 2, Hoffman, 1967). Observe that the relative characteristics of these engines do not differ by amounts significant enough to indicate a clear preference for hybrid vehicles. The selection of the gas turbine for this study, therefore, is not to be construed as definitive or final, but rather is only illustrative. The piston engine (rotary, diesel, or Otto cycle) certainly remains a strong candidate for powering the generator in hybrids.

Table 2. PROJECTED CHARACTERISTICS OF PRESENT-DAY AUTOMOTIVE POWERPLANTS UNDER 100 HORSEPOWER

	Gasoline piston engine	Diesel piston engine	Rotary piston engine	Gas turbine
Engine weight per horsepower, lb/hp	3 to 4	4 to 5	2 to 3	1.5 to 2.5
Best thermomechanical efficiency, installed under the hood	0.2 to 0.25	0.3 to 0.35	0.3 to 0.4	0.25
Least fuel consumption at optimum speed, lb/hp-hr	0.4	0.4	0.4	0.35 to 0.45
Relative fuel costs	highest	intermediate	highest	lowest
Lowest number of reciprocating and/or rotating parts between combustion chambers and power pick-off	13 (6 cyl)	13 (6 cyl)	3 (2 rotors)	1
Mass production cost, dollars/hp	2 to 3	2 to 3	2 to 3	3 to 4

The properties of the gas turbine in Table 2 vary slightly from the data on automotive gas turbines usually found in the literature (Turenen and Collman, 1965). This difference comes from calculating the entries in Table 2 for a new, simpler, and smaller breed of automotive turbine engine with carburetion fixed for constant power output, no reduction gears to the output shaft, no power transfer clutch, and omission of the many parts required for the mechanical transmission of power to the wheels.

From the gas turbine's mean value of 2 pounds per horsepower in Table 2, we may conclude that the engine weight ratio in hybrids will be about

$$A = (2 \text{ lb of eng/hp}) \times (0.029 \text{ hp/lb of W})$$

or about $A = 0.058$, nearly 6 percent of the vehicle weight.

With typical power densities of 10 to 12 horsepower per cubic foot for turbine and rotary piston machines, the engine in a full-sized hybrid car would occupy 8 or 9 cubic feet, half of the volume now taken by the engine-transmission assembly.

Generator and Motors

Alternating-current generators in aircraft today operate at top speeds of 8,000 to 10,000 rpm, half to one-third of the turbine's shaft speeds of 20,000 to 30,000 rpm. But reduction gears should be avoided in hybrid systems to achieve quietness and higher efficiency, and to reduce manufacturing costs, it also would be desirable to mount the generator's rotor directly on the power shaft. This arrangement would require a sharp upward revision of the ratio of axial length to diameter of the stator and rotor. The presently favored configurations with length-to-diameter ratios near unity can probably be slimmed down to ratios of 1.5 to 2.5 or even higher for the hybrid turbine-generator sets without incurring a weight penalty and still avoiding gear reduction.

The rated outputs of aircraft generators and of some advanced-design oil-cooled motors are plotted in Figure 7 against their weight. The mean ratio of weight to power of these generators and motors is about 1 pound per horsepower. Then the fraction of vehicle weight to be allocated first to the generator, B, and then again to the motors in the wheels is

$$B_{avg} = (1 \text{ lb of gen-mot/hp}) \times (0.029 \text{ hp/lb of W}) \times 2 \times (0.93^2 + 0.93)^{-1} = 0.032$$

In other words, about 6.5 percent (= 200 x 0.032) of the vehicle weight will be in generator and in traction motor(s).

Battery and Controls

At the bottom of Table 1 we see that the sum of component weight apportionments is

$$1.00 = A + 2B + X + 0.67$$

from which the weight ratio that can be allocated to batteries and controls in first-generation hybrids becomes

$$X = 1 - (0.67 + 0.058 + 2 \times 0.032)$$

or about $X = 0.21$.

The variable-frequency stepless and continuous controls regulating a 200-horsepower motor in a truck wheel weigh about 80 pounds (SAE, 1966). Assuming the weight of well-designed electric controls to be proportional to the controlled motor's output, we can deduce that controls will take up about 0.01 of the curb weight, leaving one-fifth of the vehicle weight for battery.

At least two distinct design possibilities for charging this sizable battery pack are available:

1. Using a fraction of the power generated by the turbine-generator. The constant power level from the generator can be selected so as to exceed by a carefully preset amount the road-driver demands for most driving situations. That portion of electrical energy from

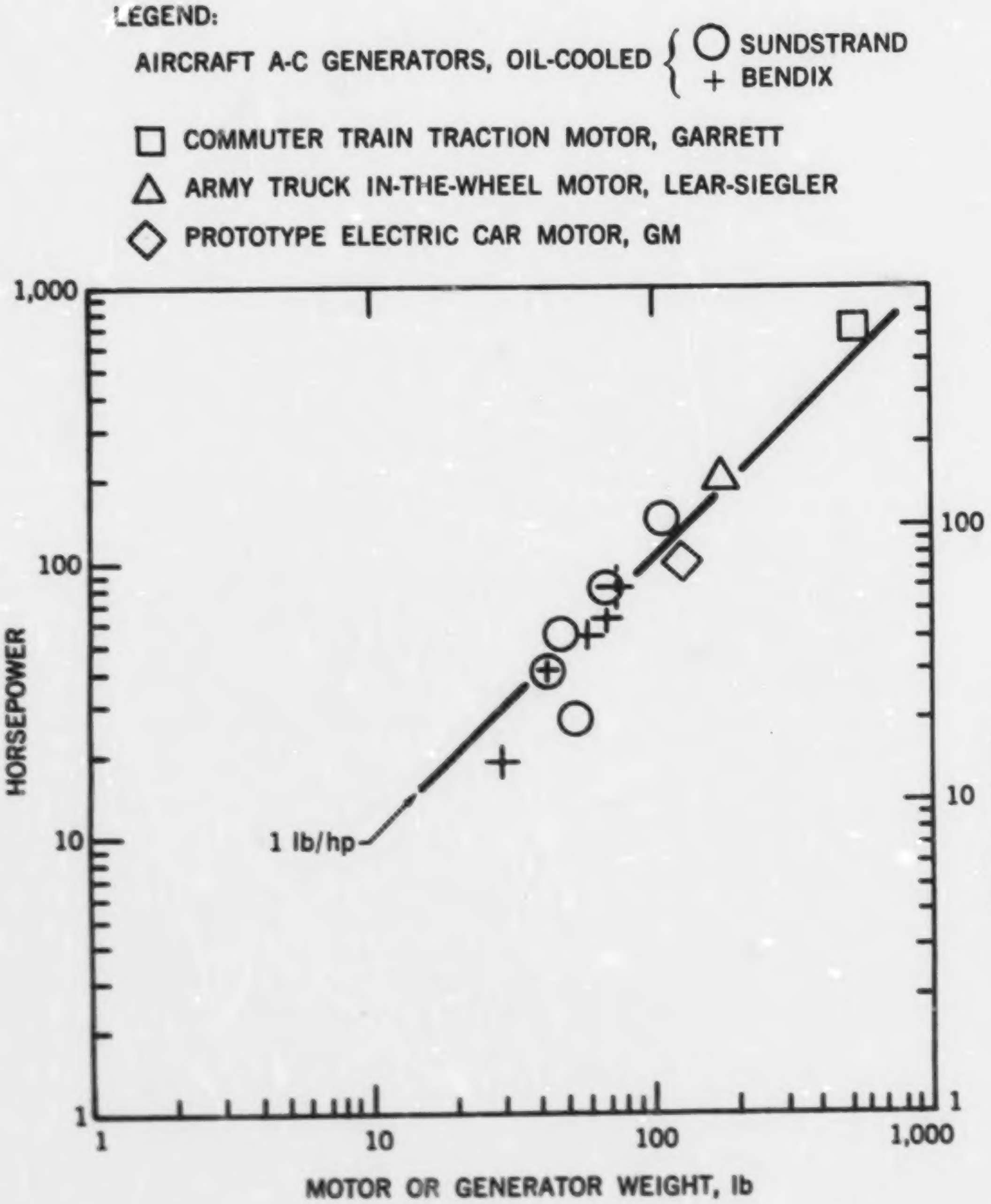


Figure 7. Weight and power of selected electric motors and generators.

the power-plant that is over and above the energy requirement for the trip can then be metered out at preset rates to the battery. An accurate allocation of power of this type should be based on a predictive catalog of vehicle usage, in the form of speed-time plots for a variety of trips, driver behaviors, locations, grades, and weather conditions.

2. Regenerative braking. An urban electric vehicle could recover about half of the kinetic energy of deceleration, presently dissipated in friction heating of brakes and engine linings (Hoffman, 1963). With a third of the urban trip time spent in deceleration, perhaps one-sixth of the energy now required for automotive travel could be recaptured into the battery. Traction motors are easily and instantly operable as generators, braking the vehicle down to 5 mph, below which speed conventional brakes and parking locks could take over. A simplified alternative design of first-generation hybrids might thus consist of the turbine-generator connected only to the driving wheels, and with regenerative braking as the sole battery energizer.

To explore the potentialities of battery installation amounting to one-fifth of the curb weight, consider a conventional lead-acid battery, capable of storing 10 watt-hours per pound, and delivering 20 watts per pound within a half-hour discharge time.

The short-time power boost derivable from the 0.20 W in batteries is then

$$0.20\ W \times (20\ w/lb) \times (0.001341\ hp/w) \text{ or } 0.0054\ W,\ hp$$

namely, a 20 percent increase in power pulses.

This power boost can raise the accelerative and passing performance and the grade-climbing ability of hybrid-power-system vehicles to that of conventional piston-engine cars over all conceivable urban and highway driving conditions (see Figure 8). The other effect of battery power augmentation is to increase the maximum speed of this vehicle to 110 mph.

The patterns in Figure 8 indicate that this first system design of hybrid power for automobiles provides too much driving power at speeds below 50 mph and not enough beyond 80 mph, even with battery boost. Follow-on parametric studies should explore power matching at 30 mph as a starting point (rather than the 50-mph base of this preliminary study), with occasional battery-power augmentation beyond 30 mph on demand. With this better balanced arrangement, we forecast that a hybrid-power passenger car will:

1. Pollute our air only one-eighth to one-fourth as much as today's conventional car.
2. Consume only half as much fuel.
3. Compare well in size, performance, and top speed.
4. Disrupt industry less than any other system in the eventual transition to all-electric cars.

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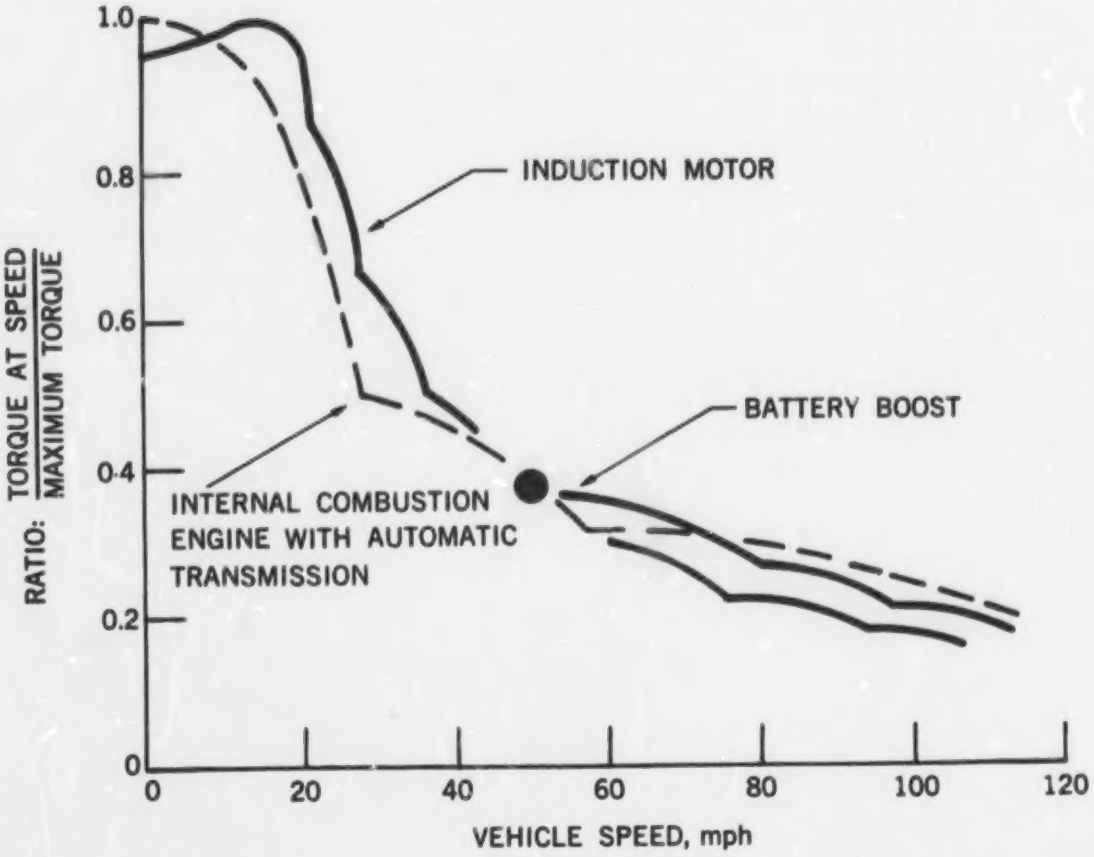

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NASA WORK ON HIGH-ENERGY-DENSITY ELECTROCHEMICAL POWER DEVICES

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To ensure crew safety during manned space flights and to maximize the probability of success of unmanned space missions, all spacecraft subsystems must have extraordinarily high reliability. In addition, each subsystem should be as small and as light as possible, to make available a maximum of space and weight for payloads. These are the general goals of the electrochemical research and development program that aims at providing reliable, high-energy, and high-power-density subsystems for space. Since the same type of criteria, together with other considerations, must be applied to automotive power plants, a number of space-oriented electrochemical projects are of terrestrial interest as well. The methods used and results obtained in these studies may find more or less direct commercial use. And even if a given space-type device is not practical under everyday conditions, the lessons learned from its development are often helpful in adapting it to meet other physical and economic requirements.

BATTERIES

Organic Electrolyte Systems

Among pertinent battery tasks is the search for high-energy-density electrochemical couples, i.e., fuel-oxidant combinations, with compatible electrolytes. For 6 or more years, the Army, Navy, Air Force, and NASA have sponsored in-house, grant, and contract work on the use of organic solvents with inorganic solutes as battery electrolytes. All of these efforts have shown how difficult it is to obtain highly pure cell components; and purity appears to be a requisite for compatibility. Even if this problem is solved, the fact remains that all organic electrolytes investigated to date have ionic conductivities so low that they are unsuitable for high rates of discharge. Thus, although high energy density may be achieved, high power density has yet to be shown. We can go even further and say that an operable, compact, high-power cell would have an inherent difficulty: Because no electrochemical reaction is 100 percent efficient, the rate at which heat is produced per unit volume in such a system must be higher than in a conventional one; hence, special engineering skill is necessary to maintain thermal control. The negative results of these efforts are valuable lessons in themselves. In addition, a potentially positive result has come from one of the contracts in this area.

Since mid-1963, Monsanto Research Corporation has been investigating their dry-tape battery or fuel cell (US Pat. 3,260,620 and

3,293,080) under various NASA contracts (currently NAS3-7624). One might have a prolonged semantic discussion as to whether this is a battery or a fuel cell. Suffice it to say that the device employs a multiple-reserve construction, i.e., the active components are packaged separately and combined only immediately before use. Because of the bulk and weight of its inevitable non-active components (packaging, drive, controls, housing), the dry tape does not appear to be applicable for 4- or 5-hour missions, the maximum duration of driving a conventional car before refueling. One of the cathodic materials studied under this task does, though, have some interesting properties that make it, as well as related substances, worth further consideration. Trichlorotriazinetrione (also called trichloroisocyanuric acid) is a solid, organic bleach that contains 85 percent equivalent chlorine on a weight basis. In combination with magnesium, for example, the theoretical energy density of the electrochemical couple alone is 750 watt-hours per pound. An electrolyte more compatible than those now available remains to be found; further, the weight of a battery would obviously be much more than that of the active materials themselves. But this bleach offers the energetic advantages of chlorine without the tankage weight penalties and the toxicity hazards entailed by the use of that gas.

I should like to suggest, therefore, that bleaches be considered as oxidants in batteries or battery/fuel-cell hybrids. If an acceptable solid electrolyte can be found, a flow-through cathode might be combined with it, through which a liquid bleach or a bleach dissolved in an inert solvent is pumped. The lightweight storage tank for the oxidizer might contain a flexible bladder so that the spent liquid can be stored in the same container before re-processing. The solid electrolyte must prevent diffusion of materials into the anode. The flow-through cathode would permit continuous flushing of the cell, and thus undesirable build-up of products could be avoided.

Alkaline Batteries

Let me now switch from a futuristic to a more immediate electrochemical system, the zinc-oxygen cell. A number of projects aimed at improving the silver oxide-zinc space battery have direct bearing on that system, particularly on a rechargeable zinc-oxygen or zinc-air battery. When the zinc anode is recharged, i.e., when zinc is electroplated from the electrolyte back on the anode, it becomes covered with uneven zinc deposits. Zinc dendrites or needles tend to penetrate the cell separator and eventually to short-circuit the cell by contacting the cathode.

In a contract with the Goddard Space Flight Center (NAS5-3908), scientists at Leesona Moos Laboratories observed three distinctive types of zinc dendrites. Mossy, pine-tree-shaped, or acicular deposits were formed, depending on the overpotential. The mossy kind, deposited at up to 0.1-volt overpotential, is least objectionable; but this means that zinc plates have to be recharged very slowly. Small hydrogen bubbles and local density differences between zincate-rich and zincate-depleted electrolytes caused localized convection at dendrite tips and thus contributed to undesirable needle growth. Once started, needles grew more easily than smooth deposits, because zincate ions diffused slowly; the needles "reached out" for more zinc. Needle growth was worst at the edges of electrodes. Masking the edges with non-porous polyethylene or other plastic was proposed as a solution to edge growth. Unsymmetrical pulse charging was suggested to the contractor, who did indeed find that 30 percent on—60 percent off resulted in lower dendrite growth than continuous charging. Thus a "half-wave" or other type of discontinuous charge may overcome some of the rate limitation set by the low overvoltage requirement for continuous charge.

A parallel effort at Yardney Electric Company (NAS5-3873) confirmed a number of these findings. In addition, examination of zinc deposits in membranes established that they penetrate by deposition within the separator rather than by mechanical puncture. High overpotential and low zincate concentration in solution are the chief causes for such harmful growth. Furthermore, the overpotential at which penetration takes place was found to be a function of the partition of zincate ions between the adsorbed state (on separator fibers) and the free state (in solution, held within the separator). The lower the partition ratio of adsorbed to free zincate, the more resistant is the membrane to zinc penetration. Although cellophane soaked in 44 percent KOH gave a ratio of only 0.03, it is not stable enough to be a good separator.

The best organic separator found thus far, for both stability and low zinc penetration, was prepared by the Borden Chemical Company. (NAS5-9107). A 10 percent aqueous solution of methyl cellulose (700g) and a 10 percent aqueous solution of (polyvinyl methyl/maleic anhydride) (300g) were mixed at 0°C. The solution was poured on a glass plate, leveled with a doctor blade, and water was allowed to evaporate before the film was stripped from the glass. Even so, the 60 or so cycles obtained with silver oxide-zinc cells would obviously be far from commercially acceptable. Relief may come from projects that started for completely different reasons.

An inorganic separator was developed by Astropower Laboratory to operate silver-zinc cells at much higher temperatures than the normal range of about 0° to 40°C. It has been incorporated into test cells (NAS3-7639) and sustained well over 1,000 cycles at 35 percent depth of discharge and 25°C; even at 50 percent depth of discharge and 100°C, it has sustained more than 250 cycles. Another inorganic separator, electrodeposited calcium hydroxide, has been studied for us by General Electric Company (NAS5-9168) and is now being further evaluated. A separator made by Radiation Applications, Inc., specifically for sterilizable batteries (JPL contract 951015) still remains to be tested for resistance to zinc penetration. In principle, however, inorganic or organic high-temperature or sterilizable separators may turn out to be tougher and longer-lived under ambient conditions than their more traditional precursors.

We have started work on primary and secondary zinc-oxygen cells for space during the past fiscal year. Of particular interest are preliminary results obtained at Union Carbide Corporation (NAS5-10247), where a zinc-oxygen 16-AH secondary cell was discharged about 20 percent in 2 hours and recharged in 6 hours. This 8-hour cycle has been repeated 14 times thus far. Such charge/discharge times approach those one might expect for everyday battery uses.

Auxiliaries and Test Procedures

Whereas the cathode of the zinc-oxygen (air) battery is only a partial product of recent fuel-cell research, the fuel cell as a whole has been incorporated into batteries, not as a power-producing but as a gas-consuming device. The gassing of zinc plates, which evolve hydrogen with almost any electrolyte under almost all circumstances, would make a sealed battery structure impossible if the gas could not be consumed again. Miniature fuel cells inserted in silver-zinc cells have operated satisfactorily for up to 1 year (NAS5-9594) and are being further developed and evaluated by Astropower and at NASA's Goddard Center. The same purpose can be achieved by fuel-cell type auxiliary electrodes that have been used by General Electric Company (NAS5-3669), among others, to remove both hydrogen and oxygen from sealed silver-zinc cells.

The question of charge control is not simply answered; the correct method depends on the size of the power supply and on the time available for recharging, according to a General Electric Company report on contract NAS5-9193. They recommended constant current charge for small (up to 15 watt) nickel-cadmium power sources and 1-hour charge time; and constant voltage/coulometer cut-off with auxiliary gas-recombination electrodes for larger power supplies. A simple electrochemical coulometer made from commercial cadmium plates was described by E. R. Stroup in NASA report X-716-66-462. It functioned well with nickel-cadmium batteries at 0° to 25°C for at least 1 year. Although these charge-control devices and procedures were developed specifically for nickel-cadmium batteries—the space workhorses—I cite them because they indicate what can be done and must eventually be adapted to ensure safe and reliable operation of other battery power plants.

Like all battery manufacturers and many other battery users, we have our own test programs and procedures. An original contribution to this type of activity arose from a brief contract with Radio Corporation of America (NASw-1001) to develop statistical methods for correlating the voluminous test data. It is a nondestructive procedure for determining the quality of a battery. Though perhaps not an original discovery of Mr. J. H. Waite, (it appears to have been used on relays in WW II), it is potentially applicable to any mass-produced item and looks particularly valuable as a deterministic, instead of the usual probabilistic, statistical approach.

Briefly, the procedure is as follows: A statistically meaningful sample of a population is tested to destruction under normal operating conditions, while significant data are being recorded, particularly frequently during the initial test period. The data are manipulated to show differences, for the initial portion of the life test only, among samples that passed and those that failed for a variety of reasons. One can then take another member of the same population, obtain initial life data only, and match the results to those previously obtained, in order to predict whether this specific member will complete its mission or, if not, what will cause it to fail.

It is not yet known whether a general mathematical basis, similar to conventional statistics, can be evolved for this approach. Nor are the physical details for meaningful battery testing fully explored as yet. Preliminary indications from nickel-cadmium battery tests are that the method may be made fail-safe; i.e., although tests showed likely premature failure, some battery packs completed their mission; but no "sound" batteries, according to prediction, failed.

FUEL CELLS

For the present, at least, NASA is concentrating on one type of fuel cell only, the hydrogen-oxygen cell with alkaline electrolyte. Although the Bacon-type intermediate-temperature (250°C) fuel cell for the Apollo spacecraft needs no added catalyst (the nickel electrodes are catalytic enough at that temperature), low-temperature fuel cells, operating at temperatures up to about 150°C, do need catalysts on both anode and cathode. The greatest problem of inefficiency consists of the voltage loss at the cathode of low-temperature systems, where 0.2 to 0.3 volt per cell is lost as soon as any power is drawn. This is true even for the best platinum or silver electrodes.

To overcome this loss, I started a program at Tyco Laboratories in mid-1965 (NASw-1233) on preparation and screening of a series of alloys that are potential cathodic electrocatalysts. Thus far, osmium and certain titanium alloys have been identified as promising materials. They are perhaps of dubious commercial value. On the other hand, nickel carbide was found to be about 90 percent as good as platinum. That is not good enough for space, but in view of its price and availability it may attain commercial importance. I hasten to add that, thus far, it has been too unstable to be useful for any length of time. Similar preparations are being made for us by the Bureau of Mines (Contract W 12,300) and being evaluated for possible ground applications by six firms. We furnish free catalyst samples to them, in return for which we obtain the test results. Since this mutual aid program has just begun, it is too early to speculate on the results.

Another problem of gas-fed fuel-cell electrodes has been with us for a long time. In 1839, Sir William (later Lord Justice) Grove mentioned, in describing the very first hydrogen-oxygen fuel cell, that the seat of the electrochemical reaction is at the three-phase interface. He thought that power production occurs where the gaseous reactant, liquid electrolyte, and solid electrode meet. Though he was almost right, modern work has shown that the locus of reaction is just below this boundary, in a thin film of electrolyte above the visible meniscus. Gas does not react at the solid surface until after it has been dissolved in the electrolyte.

On a grant to Professor Bockris at the University of Pennsylvania (NsG-325), a graduate student has been working on the behavior of the pore of a gas-fed fuel-cell electrode, deepening the insight gained into this problem by Professor Meissner's students at Massachusetts Institute of Technology, Dr. Will at General Electric Company, and others. Mr. Cahan observed boiling of the meniscus in a model pore. Further work showed that about 90 percent of the current was produced in a meniscus ring about 10^{-6} centimeter thick. In other words, only about 5 percent of the catalyst now used in fuel-cell electrodes appears to perform its function; the rest is wasted. This study points out that extremely thin electrodes would suffice for the electrochemical reaction.

On the other hand, the thinness of the active layer may simply be the result of the way we operate fuel cells today. They are still being built according to Grove's recipe, maximizing the three-phase interface. If the active layer is so thin only because all of the sparsely soluble gas is used up in that region, then it may be possible to improve the power density of a fuel cell by separating the two operations, gas saturation of electrolyte and electrochemical reaction, that are now so closely coupled in the electrode. This decoupling does not make sense for a single cell, but it may result in advantages for a stack of 30, 60, or even more cells. We now have three contractors taking a look at the engineering problems of novel types of fuel cells that would break with the Grove tradition. Furthermore, new work on optimization of porous electrodes is underway. In general, fuel cell power plants of today are not much more than assemblies of slightly scaled-up laboratory cells. A good deal of imaginative chemical engineering remains to be done.

But, though the core of a fuel-cell plant represents a fairly loose coalition of individual cells thus far, their combined behavior is far from that of the same number of single cells. Something always gets lost in the stacking of them, and it doesn't much matter which kind of basic building block is being used. Whereas single cells might perform well for a year or even several years, the very best stacks have only lasted for hundreds (say 1,800) instead of thousands of hours so far. The reasons for failure depend on the type of cell, on the method of operation, and on the control devices, to name only the most obvious. Not enough full-size stacks have yet been built to know details about the behavior, reasons for, and mechanisms of failure of any fuel-cell system in existence today.

The first extensive fuel-cell stack test is being carried out by Allis-Chalmers Manufacturing Company (NAS8-2696). We are doing here what has been done with batteries routinely for years. However, in view of the much higher cost of these stacks, the program now comprises only eight of them. The stacks are being built as much alike as possible, though we will take advantage of improvements that become apparent as we go along. Each stack will be run under standard conditions for the first 200 hours to ensure uniformity. After this check-out procedure, each stack will be tortured in a different manner until failure: repeated starts and stops, simulated external short circuit, unbalanced gas pressure, improper water removal, excessive temperature, etc. The results will permit a rather modest statistical assessment of full-size stacks, their uniformity, their capability to withstand abuse, their mode of failure under different stresses, their safety, and their reliability. Though this is the first such systematic evaluation of fuel-cell stacks, it will have to be repeated, and on a much larger scale, if commercial use of them is ever to become widespread. I hope that this exercise will set a helpful precedent and that many of the results and conclusions will be applicable to other than the specific system with which they will have been obtained.

Although the Allis-Chalmers Manufacturing Company system still uses ordinary asbestos to contain the electrolyte, we already know that a considerably improved material must take its place, if long-term operation of matrix-type cells is to be achieved at minimum rates of degradation. Several contractors, among them Electro-Optical Systems (NAS3-2781), are studying composite asbestos matrices or completely different substances for this purpose. In addition, Union Carbide Corporation is upgrading its free-electrolyte fuel cell for the high power and energy densities required in space (NAS3-9430). It will be interesting and instructive to compare the performance and longevity of this modified equipment with that using an electrolyte matrix, since both will be tested under very similar load conditions.

CONCLUSION

This summary of space-oriented electrochemical research and development, aimed at producing compact, lightweight reliable power sources, clearly shows that we have no ready-made, 50- to 100-kilowatt product directly applicable to consumer uses. Yet, I hope you will agree that these ideas, approaches, data, and devices can contribute to our obtaining considerably improved batteries and fuel cells, be they upgraded conventional ones or radically new ones. This program should help solve some long-standing problems, lead to simplified controls, and perhaps result in easier operability and maintainability of such power plants. We do, of course, hope that some of the concepts will end up as practical hardware that can be applied where and when electric vehicles may prove to be feasible.

POTENTIAL BATTERY SYSTEMS IN VEHICLE PROPULSION

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In the past most efforts to study the potential opportunities for electric vehicles have centered on the lead-acid battery as the energy source. This choice was based primarily upon the low cost and ready availability of the lead-acid battery. However, the relatively low energy content of the lead-acid system resulted in vehicles with very limited ranges; further, the weights of the batteries were extremely great, compared to the weight of the very high-capability, gasoline-powered, internal combustion engine. During the period of 1958 to 1962, at least three such converted vehicles powered by lead-acid batteries were built by the General Electric Company. These vehicles were plagued by limited range, although acceleration and top speed were adequate for ordinary city driving. Nonetheless, their unpredictable range made these test vehicles highly unsatisfactory. At that time, no other battery candidate systems were available to consider as alternative power sources. Little or no analytical work was done to predict vehicle properties in advance of building such vehicles. As a consequence, interest in battery-powered vehicles declined at General Electric and also at other organizations that had shown early interest.

In England, where other economic considerations are involved, engineering development and manufacture of electric vehicles has proceeded with considerable success. Delivery trucks powered by lead-acid batteries have had broad acceptance in Great Britain.

As research and devedopment on fuel cells increased in the early part of this decade, there came an awareness of the very great desirability of this power source for vehicle propulsion. The successful application of fuel cells to the Gemini space flights increased the public interest in the fuel cell. Nonetheless, the questions of cost, life, simplicity, and reliability of fuel cells have precluded their use in vehicles during the next few years on a large commercial scale.

Within the past 2 years the development (to the point of feasibility demonstration) of the zinc-air battery, the sodium-sulfur battery, and the other existing high-energy-content systems has established a new technological base for a variety of concepts of an electric-powered vehicle. Additionally, the widespread concern over pollution of the air by gasoline-powered internal combustion engine systems has considerably increased the interest in electric vehicles.

It is natural that analyses of vehicle systems at General Electric involved the transportation, battery, and systems competence of the Company. The analyses presented here are based on studies of the zinc-air battery, because a large amount of background information existed at General Electric. The techniques are applicable to any battery system, however, provided the investigators have sufficient technical information concerning the battery.

For initial consideration, Figure 1 shows the forces required to accelerate a 2-ton vehicle as a function of its speed. The linear portion just below 1,200 pounds of force is established by an initial acceleration requirement (in this case, 9 mph per second) and the current limit for the two direct-current traction motors that were assumed to power the vehicle. Also plotted in Figure 1 is the drag force. The accelerating force is chosen so that it crosses the drag force curve at 80 mph. The so-called balancing speed of 80 mph is chosen so that some acceleration will be available at the design cruising speed of 50 mph.

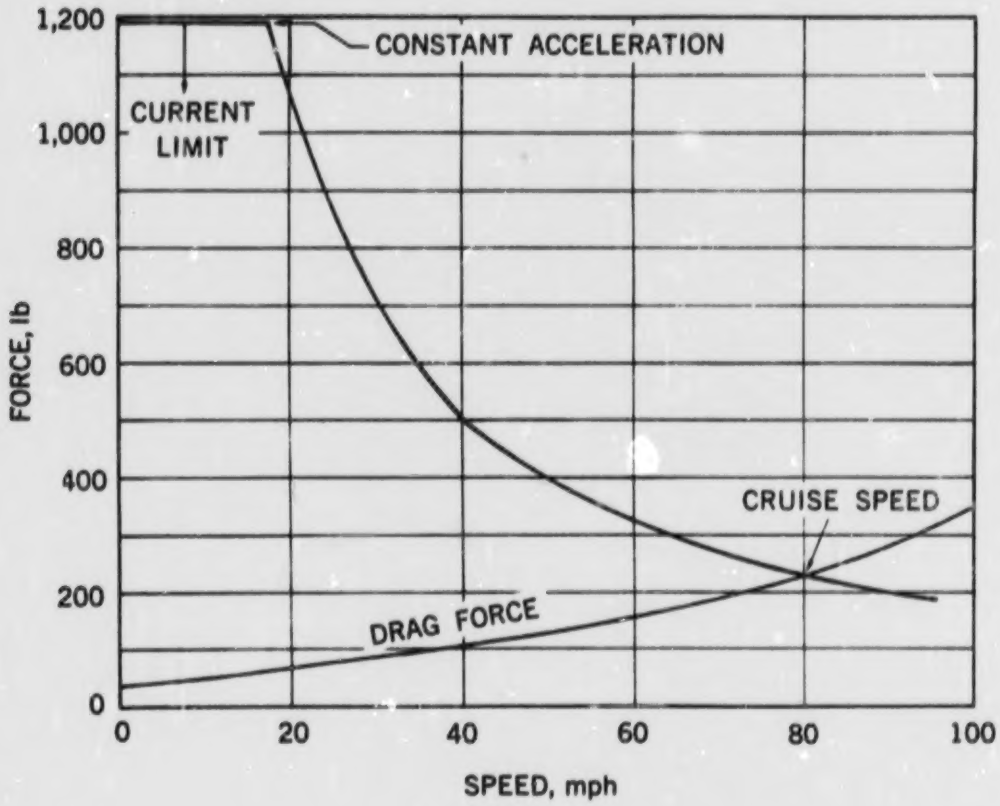

Figure 1. Acceleration force vs. speed for 2-ton vehicle.

In Figure 2, the information of Figure 1 is replotted as power against speed. About 50 kilowatts of power is required to reach the balancing speed of 80 mph. To proceed further in this analysis, let us examine the data of Figure 3. At the top is plotted the acceleration to 50 mph, followed by a period of constant (level-terrain) cruising at 50 mph, and then by braking at a constant rate. Braking deceleration at 5 mph per second was assumed, but the actual value is not important to the analysis. The middle section of Figure 3 represents the motor current divided into both armature and field currents, assumed to be controlled separately. In this scheme the armature current remains constant throughout the acceleration and then drops to that current level required to maintain the constant speed. On the other hand, the field current is constant through the constant initial acceleration period, then drops until the constant-speed portion of the cycle is reached, and then increases slightly for the constant-speed part of the mission. In the analysis no regenerative braking was assumed, and hence the current in the two motors in the vehicle will drop to zero when braking commences. In the lower section of Figure 3, the power delivered by each motor is shown through the cycle. The top power level does not necessarily represent motor sizes. Traction motors can withstand prolonged periods of overload. The sizing of the motors requires sophisticated engineering judgments that need not be discussed here.

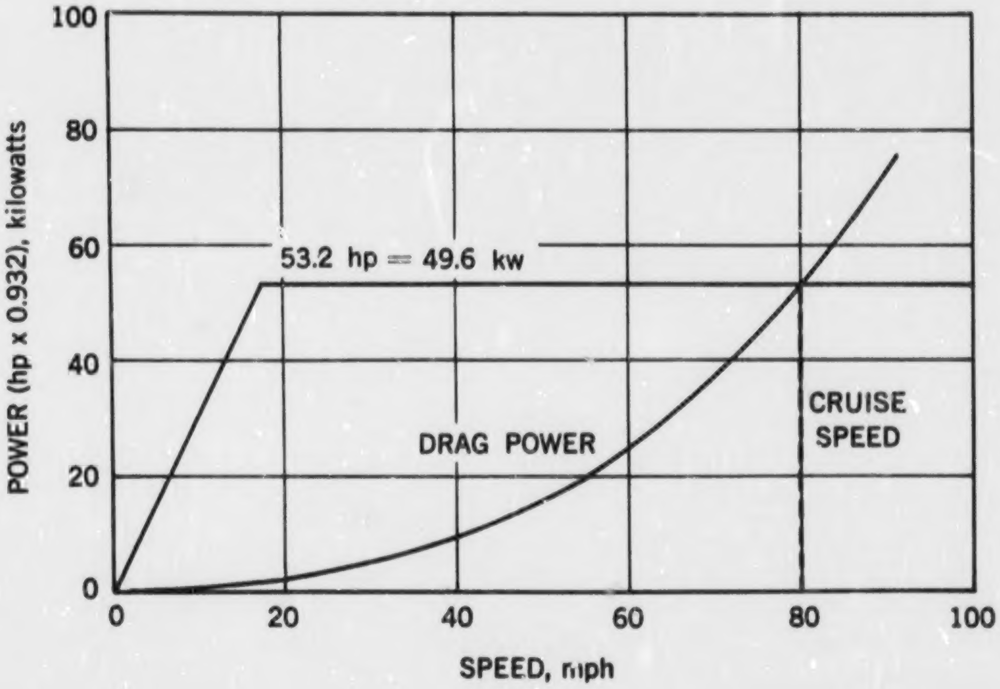

Figure 2. Acceleration power vs. speed for 2-ton vehicle.

Mathematical models were established for these types of vehicles based upon the considerations just discussed, and computer programs were established. For a typical analysis, we selected a 2-ton vehicle with a 1,000-pound zinc-air battery as its power source. Some properties of the battery must be known to complete the analysis. These data include polarization curves, power-rate data, and voltage cut-off level.

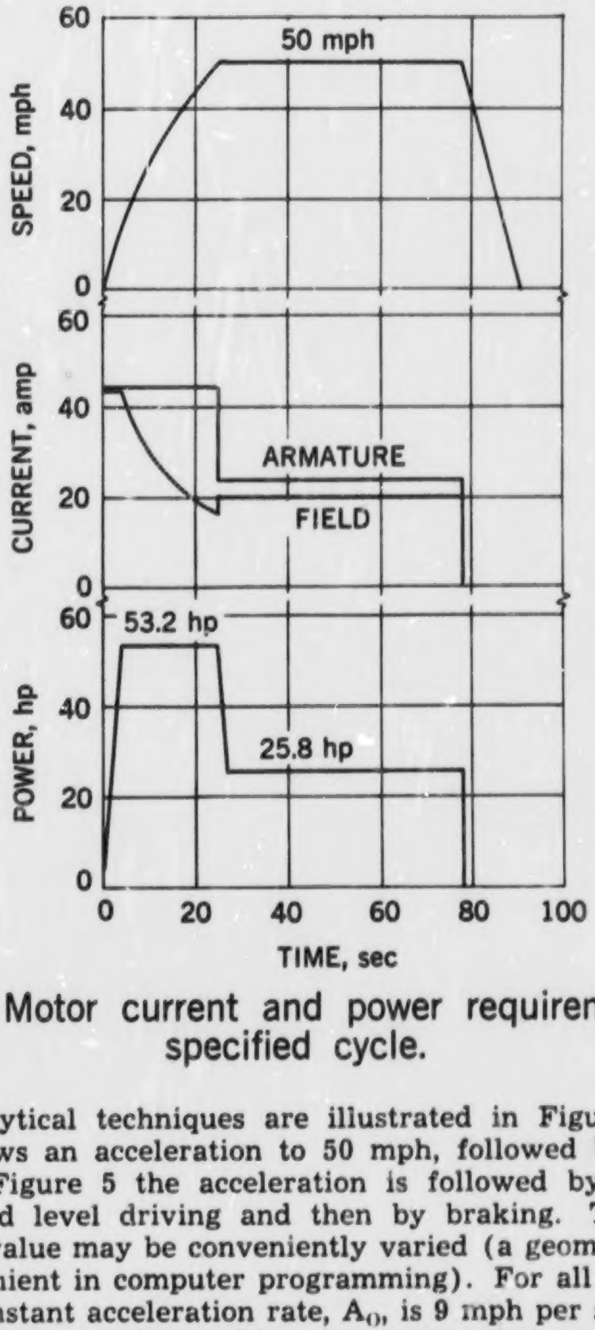

Figure 3. Motor current and power requirements for a specified cycle.

The analytical techniques are illustrated in Figures 4 and 5. Figure 4 shows an acceleration to 50 mph, followed by immediate braking; in Figure 5 the acceleration is followed by a period of constant-speed level driving and then by braking. The constant-speed range value may be conveniently varied (a geometric progression is convenient in computer programming). For all of these runs the initial constant acceleration rate, A_0, is 9 mph per second. Table 1 summarizes the typical vehicle properties that were commonly employed, the input data, and computed results for the vehicles.

Of greater significance for the battery problems are the data in Table 2. In this table the miles per cycle, that is, the distance as represented by the ordinate for the cycles of Figures 4 and 5, are

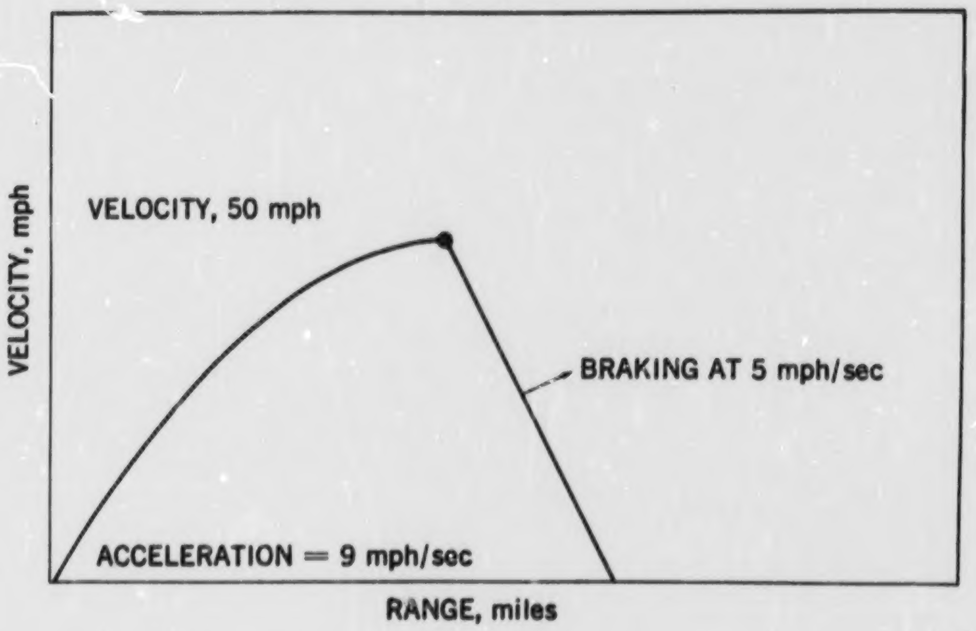

Figure 4. Acceleration of a 2-ton vehicle with a 1,000-lb zinc-air battery to 50 mph followed by braking.

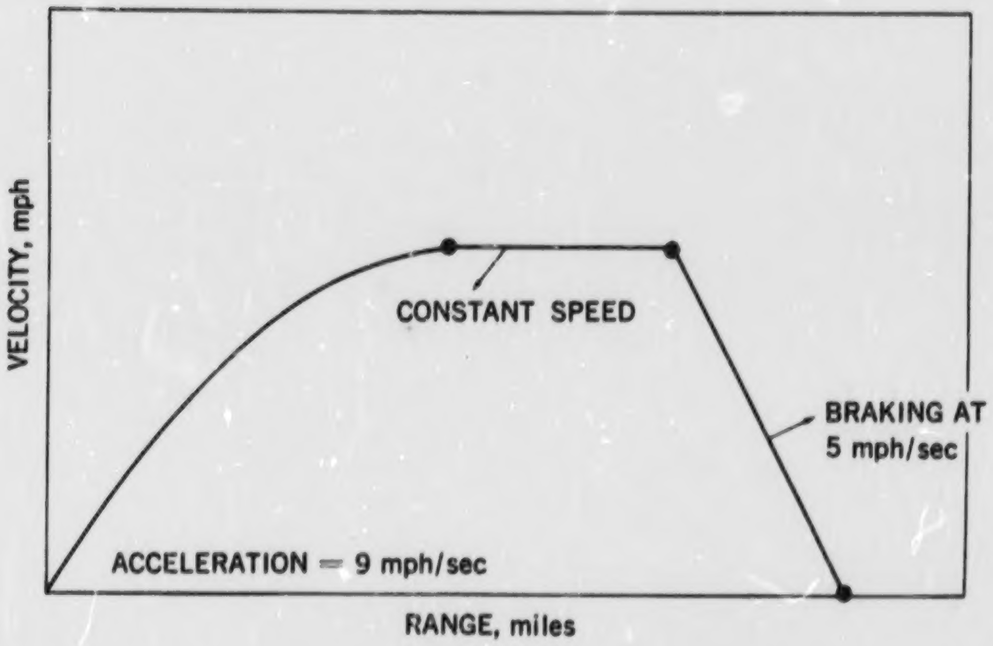

Figure 5. Acceleration of a 2-ton vehicle with a 1,000-lb zinc-air battery to 50 mph followed by constant speed driving and then braking.

Table 1. TYPICAL VEHICLE PROPERTIES

Program constants	
Balancing speed on level load, mph	80
Retardation (braking rate), mph/sec	5
Input Parameters	
Gross weight of car, tons	2
Initial acceleration, mph/sec	9
Weight of Zn-air battery, lb	1000
Cruising speed, mph	50
Propulsion system potential, volts	72
Computed Results	
Max. power/motor at wheel rim, hp	26.6
Specific load at full power, w/lb	49.6
Speed to reach full power, mph	11.2
Acceleration on reaching full power, mph/sec	8.98
Current drain at full power, amp	689
Weight of control, lb	44
Volume of control, in.^{3}	1096
Acceleration on reaching cruise speed, mph/sec	1.4
Power/motor to maintain cruise speed, hp	8.45
Current drain at cruise speed, amp	218.7
Specific load at cruise speed, w/lb	15.7

tabulated, as is the average speed, the range attainable for that particular cycle, and the computed weight of motors and gears. Note that as the number of miles per cycle increases the range attainable with the fixed weight of batteries also increases.

Since the power requirements of the motors are accurately known as the vehicle is accelerated and run at the top speed, from the computer program results one can calculate the amount of energy required for any specific mission within the framework described. One can also obtain the fraction of total battery energy (or capacity) required for each accelerate/brake or accelerate/cruise/brake situation. These energy requirements as fractions of battery capacity for a given distance are easily summed to synthesize range values for any mission. Obviously, for a given size, the missions that involve more stops and starts give shorter range values than do those missions in which most of the total distance traveled is at the cruising speed. The utility of such a system of calculations is that one can calculate vehicle properties in terms of range for a desired mission, rather than for average missions, which are generally unrealistic.

Table 2. SAMPLE VEHICLE PROPERTIES FROM COMPUTER PROGRAM

Miles per cycle	Avg speed, mph	Range, miles	Weight of gears and motors, lb[a]
0.21	29	67	
0.25	32	77	436
0.32	34	91	417
0.4	37	105	400
0.5	39	120	383
0.63	40	135	366
0.8	42	151	350
1	43	166	335
1.6	45	193	308
2	46	205	297
2.5	47	215	287
4	48	232	270
5	48	239	264
10	49	252	249
16	49	258	243
20	49	260	241
25	49	262	239
40	49	264	237
50	49	265	236

[a] This weight is for continuous duty at the specified duty cycle for a direct-current, two-motor traction system.

The effect of top speed on range is illustrated in Figure 6. The ranges for 50-mph and 70-mph cruise speeds are given as a function of miles per cycle. Other calculations show that the range is further decreased by increased cruising speed as the vehicle weight is increased. This appears to be the case even if the total weight of batteries is proportionately increased.

The properties of the zinc-air cell systems of most interest in this analysis are represented graphically in Figure 7, in which are plotted both the polarization curve for a General Electric zinc-air battery and the energy content curve for the same battery.

These properties may be combined as illustrated in Figure 8, in which the energy content in watt-hours per pound is plotted against the power density expressed as watts per pound. The portions of the curve of interest for acceleration power and for range energy are indicated. Since a combination of these properties is clearly required for vehicle propulsion, a hybrid power-source system is suggested. Because high energy content and high power density generally are not compatible in battery systems, a dual battery system may be required. These properties are illustrated in Figure 9, in which current is plotted as a positive quantity in both directions

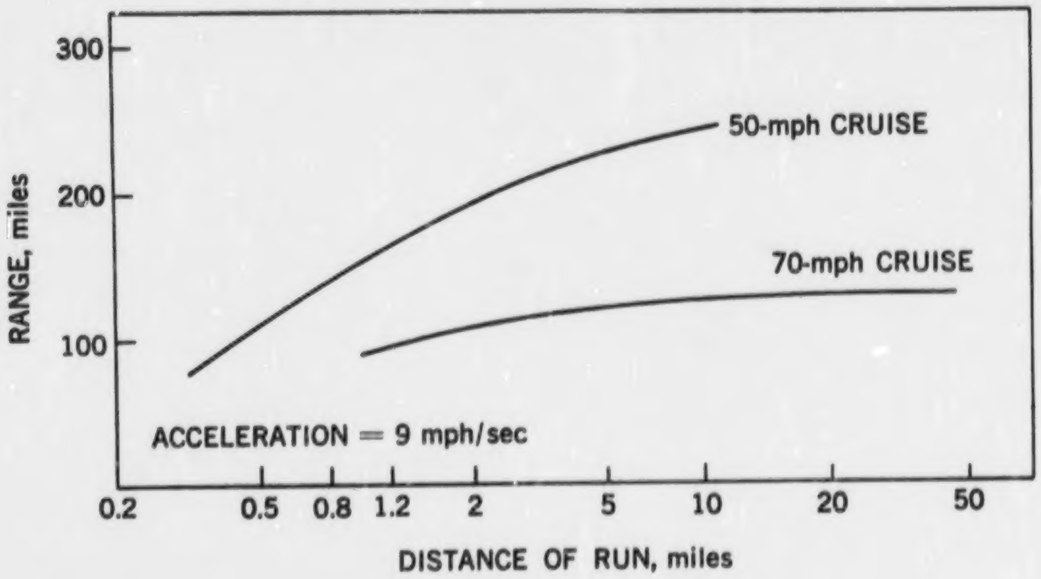

Figure 6. Variation of range of a 2-ton vehicle with a 1,000-lb zinc-air battery over various run (miles per cycle) ranges.

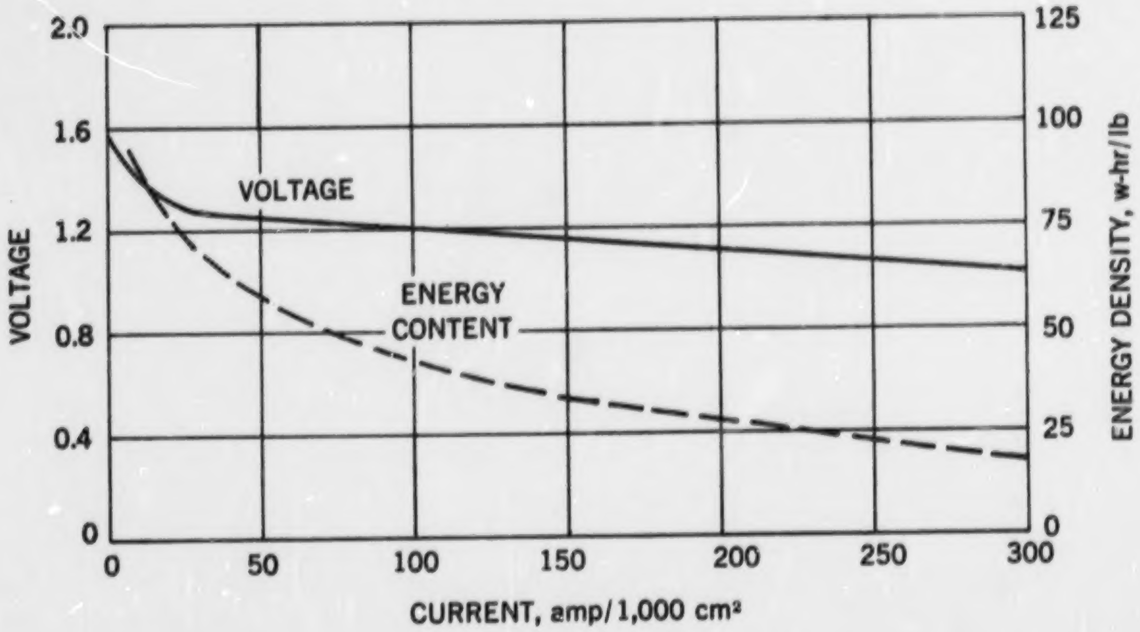

Figure 7. Polarization curve and energy content of zinc-air cell.

from the voltage axis for a high-energy-content battery and for a high-power-density battery.

In such a system the high-energy-content power source could be a battery or a fuel cell, and the other power source could be any battery (or other system of high power capability) capable of delivering high currents to supply acceleration power. The high-energy power sources can then be used to recharge the high-current (high-power-density) source at the stop condition if the latter power source is a battery. This will be done at relatively high efficiency because of the operation of the high-energy-content system near the open-circuit voltage.

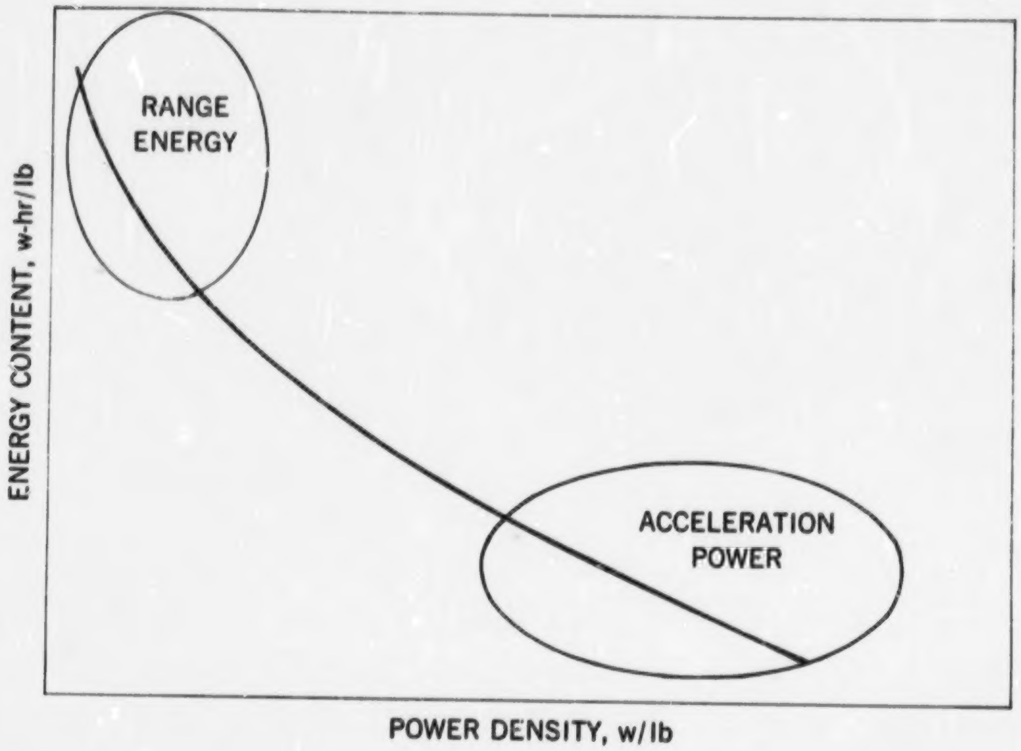

Figure 8. Watt-hours per pound vs. watts per pound for zinc-air batteries.

In summary, a computer program has been established with which the properties of electric vehicles can be estimated. Preliminary studies based on zinc-air battery systems have been made in which the vehicle range for any mission can be calculated. The utility of hybrid battery systems or battery and fuel cell systems has been shown.

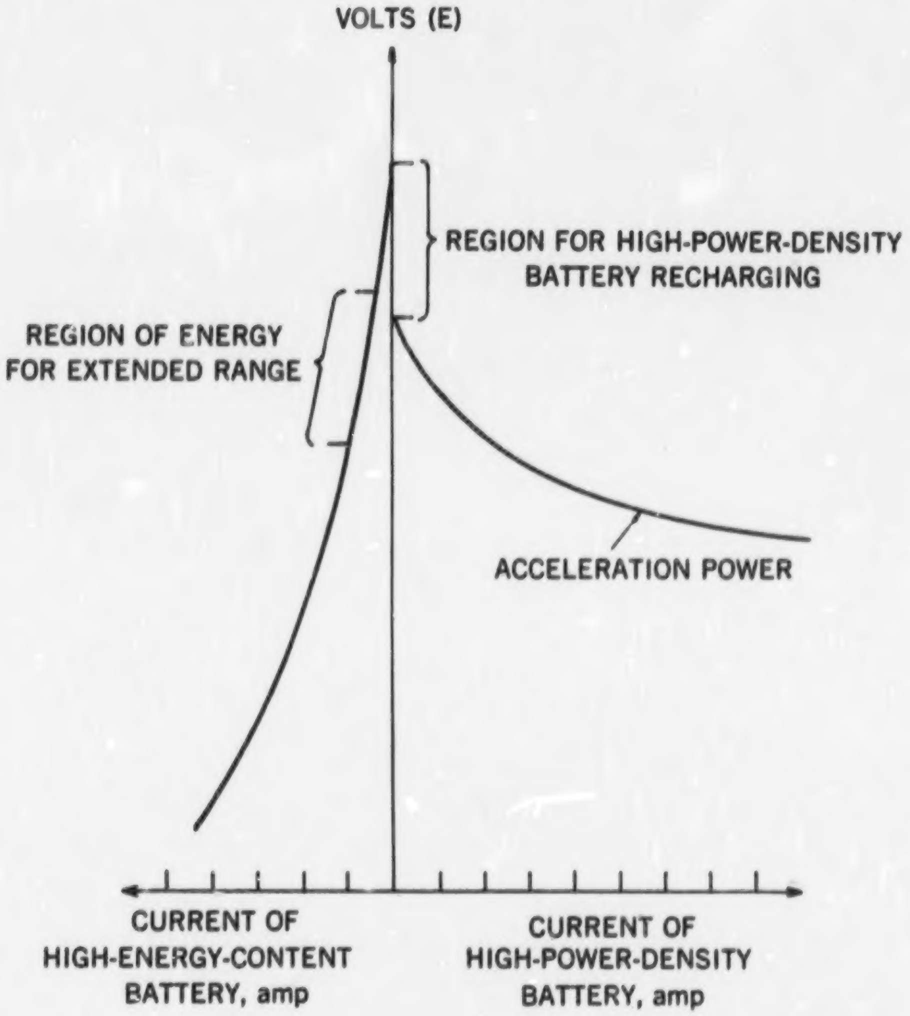

Figure 9. Two-battery hybrid system polarization curves.

ACKNOWLEDGEMENT

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BATTERY-POWERED ELECTRIC VEHICLES

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The Electric Storage Battery Company (ESB) has gained years of practical experience with various types of battery-powered vehicles now operating and now is engaged in research and development on new power sources for electric vehicles.

We have supplied power systems for three types of electric vehicles now in operation. In the first category are battery-powered fork-lift trucks and golf carts. About 100,000 to 200,000 units of each type are in use in the United States, an indication that quiet, clean operation combined with low maintenance and low operating costs makes battery power attractive to many users. Battery-powered vehicles have proved themselves in many other applications including mining equipment and in-plant utility vehicles. The principal battery used for these types of applications is lead-acid.

ESB increased by 18 percent the energy output per unit volume of its Exide-Ironclad cell construction with improvements introduced between 1952 and 1954; we further increased the energy output by another 43 percent with improvements introduced between 1954 and 1966. At present, this long-life, deep-cycle type of lead-acid battery delivers approximately 1.4 watt-hours per cubic inch at the 6-hour rate.

The second category of electric vehicles for which ESB can provide operating data is the delivery truck. Vehicles of this type have used Exide-Ironclad batteries since 1910. Our most recent experience is with route trucks manufactured by Battronic Truck Corp., an ESB affiliate. Some of these trucks have been in use for more than 3 years. The power system is an 84-volt Exide-Ironclad battery of either 425 ampere-hours (42TSC11) or 340 ampere-hours (42TSC9). The smaller battery delivers approximately 11 watt-hours per pound.

In typical multi-stop delivery service, such as on milk or bread routes, the present Battronic trucks have a loaded range of about 40 miles and a top speed of about 25 miles per hour (Figure 1). The maximum gross weight is 9,500 pounds, including the load. Combined load and battery weight is 5,000 pounds; route requirements determine the size of the battery, which weighs 2,000 to 3,000 pounds. Data on these vehicles are summarized in Table 1.

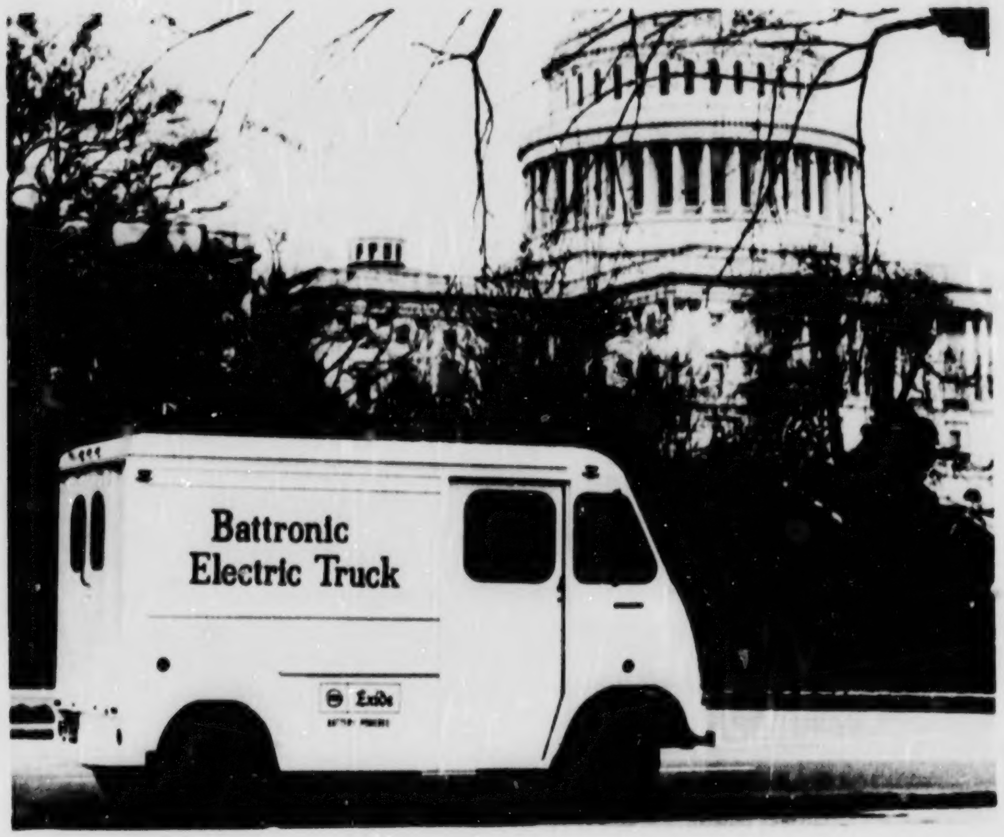

Figure 1. Truck powered by an 84-volt Exide-Ironclad battery.

Table 1. OPERATING CAPABILITIES OF A DELIVERY TRUCK POWERED BY LEAD-ACID BATTERY

Load capacity: 2,000 to 3,000 pounds
Gross maximum weight (vehicle and load): 9,500 pounds

	Present	Presently possible
Top speed on level road (loaded)	25 mph	35 to 40 mph
Acceleration	1.5 mph/sec	1.5 mph/sec
Hill climbing speed (10% grade)	12 mph	14 mph
Maximum range on one charge of the battery (loaded, 8 stops per mile)	40 miles	60 miles
Time required for full charge of the battery (after complete discharge)	up to 10 hours	up to 10 hours
Type of motor	series traction	compound traction
Type of controller	contractor	solid state

TRUCK IN USE AT MAPLEHURST FARMS DAIRY, LINCOLN, R.I.

Operating experience has shown over-all costs (depreciation included) of $4.76 to $6.00 per day for an electric truck, compared with $7.00 to $9.00 per day for a gasoline truck on similar routes. Thus, the possible savings are $1.00 to $4.25 per day. Projected improvements in the lead-acid batteries, the controller, the motor, and the chassis are expected to yield speeds up to 35 to 40 mph and a maximum loaded range of about 60 miles. Many delivery routes and other functions could be handled by the existing or improved trucks. Benefits that would be realized are lower operating costs and reduced noise and air pollution.

The third type of electric vehicle for which we have operational data is the small personal car, such as the ESB-Exide Electric Car (Figure 2). This vehicle operates with twelve 6-volt golf-cart-type batteries (3LDT-9), which produce a total of 10.1 kilowatt-hours. Without sophisticated electronic controls, aerodynamic streamlining, improved motors, or special tires, this vehicle has a range of 35 miles and maximum speed of 40 mph (Table 2). The economy of operation is shown in Table 3. Projected improvements are expected to result in a maximum-load range of 50 to 60 miles and a top speed of 50 mph (Table 4).

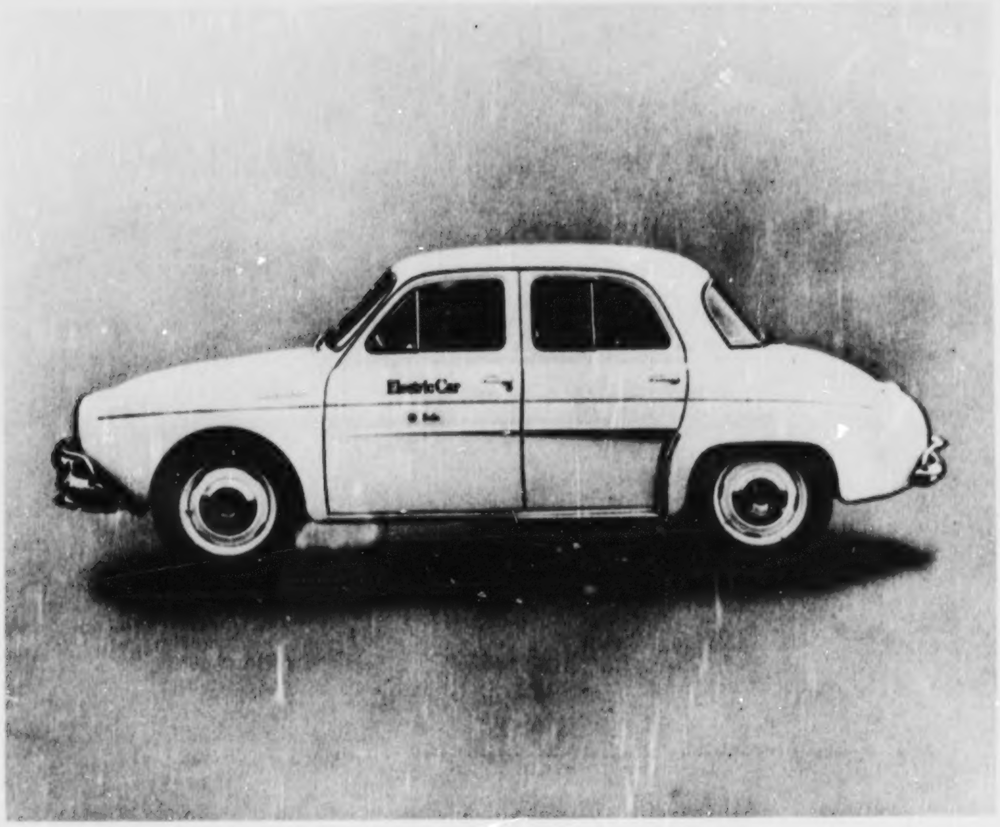

Figure 2. Electric car powered by twelve 6-volt golf-cart-type batteries.

Table 2. PERFORMANCE CHARACTERISTICS OF PRESENT ESB-EXIDE ELECTRIC CAR

Maximum speed: 40 mph on a level road
Range: 25 to 35 miles per battery charge
Acceleration: from stop to 20 mph in 3 seconds
Hill-climbing rate: 10 percent grade at 20 mph

Our total experience with the three types of electric vehicles so far discussed is summarized in Figure 3. This figure, a plot of range versus the ratio of available power to total vehicle weight, shows the effect of weight and acceleration losses on the range of vehicles at a speed of 30 mph. Other charts at other speeds show that at a ratio of 4 watt-hours per pound, with a vehicle traveling at 15 mph, the range without stops would be 60 miles; at 30 mph, 50 miles; and at 45 mph, 42 miles. Then range is reduced as the number of stops increases. This ratio of 4 watt-hours per pound of total vehicle weight is approximately the ratio for existing vehicles.

Table 3. ECONOMY OF OPERATION OF PRESENT ESB-EXIDE ELECTRIC CAR

Estimated cost of operation for 5 years driving 5,000 miles per year	
Electricity	$375
Battery replacement	450
Licenses	50
Greasing	12
Repairs with labor	
Contactor tips	35
Motor brushes	17
Total	$939
Estimated cost per mile:	3.5¢

[a] The ESB-Exide Electric Car uses 0.75 kilowatt-hour of alternating current for each mile of driving. Based on a household rate of 2¢ per kw-h, the cost of electricity for recharging the battery is 1.5¢ per mile.

Table 4. PROJECTED PERFORMANCE CHARACTERISTICS OF SMALL "URBMOBILE" POWERED BY EXISTING LEAD-ACID BATTERIES

Maximum speed: 50 mph on a level road
Range: 50 to 60 miles per battery charge
Acceleration: from stop to 20 mph in 3 seconds
Hill-climbing rate: 10 percent grade at 30 mph

With present technology, the speed and range of electric vehicles are limited by the energy available in the power source (as shown in Figure 3). With the power sources now available on a production basis, economics pretty well limit the choice to the lead-acid battery system with the limitations of speed and range indicated.

Although ESB is continuing research and development on the lead-acid, nickel-iron, nickel-cadmium, silver-zinc, and silver-cadmium systems, it is likely that improvements in the performance and economics of these systems will be incremental. It appears that large increases in range or speed of an electric vehicle will come only with the introduction of a new power source that can be produced cheaply enough to provide energy at about the same cost per kilowatt-hour as the lead-acid battery, i.e., in the range of $50 to $100 per kilowatt-hour initial cost. A number of other requirements must be considered, such as power density, convenience of use, start up, and life.

ESB is investigating, in research and development stages, a number of systems that show some promise for application to electric vehicles. These include fuel cells, metal-air cells, non-aqueous systems, and cells with organic active materials. At present, all of these systems show some limitations for vehicle applications.

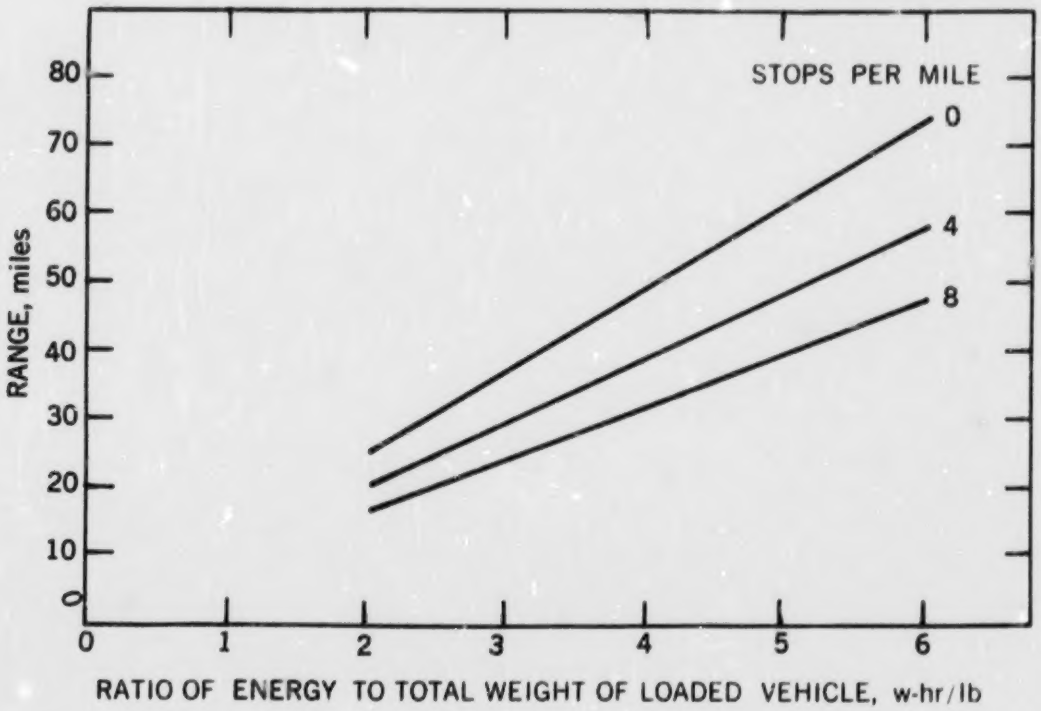

Figure 3. Effect of vehicle weight and acceleration loss on range (30-mph cruising speed).

Fuel cells are currently unattractive in terms of cost, life, convenience, and power density. Since fuel cells have received considerable attention generally, we will briefly, describe the work of ESB on other systems, with comments about their future possibilities.

ESB has been investigating metal-air cells for more than 10 years by several approaches involving both static and dynamic systems. Most of our efforts have been concentrated on the zinc-air system, which seems to offer the best combination of characteristics.

Our most recent zinc-air projects have been in static systems incorporating very thin air electrodes with a third electrode for recharging the zinc electrode. A typical seven-cell secondary battery of this type is shown in Figure 4. The output performance, power density as a function of current density, is shown in Figure 5, which indicates an average peak power for the secondary battery of 88 milliwatts per square centimeter. This figure also gives the data for a primary zinc-air cell of similiar design and shows that even greater output is possible with the present secondary design. As an example of the progress that has been made, the lowest curve indicates the performance of an earlier cell.

The effect of temperature on performance is shown in Figure 6. These data were obtained at close to isothermal conditions, i.e., the battery was not permitted to heat up as a result of chemical inefficiencies. Even under these very severe conditions, useable power was obtained at low temperatures.

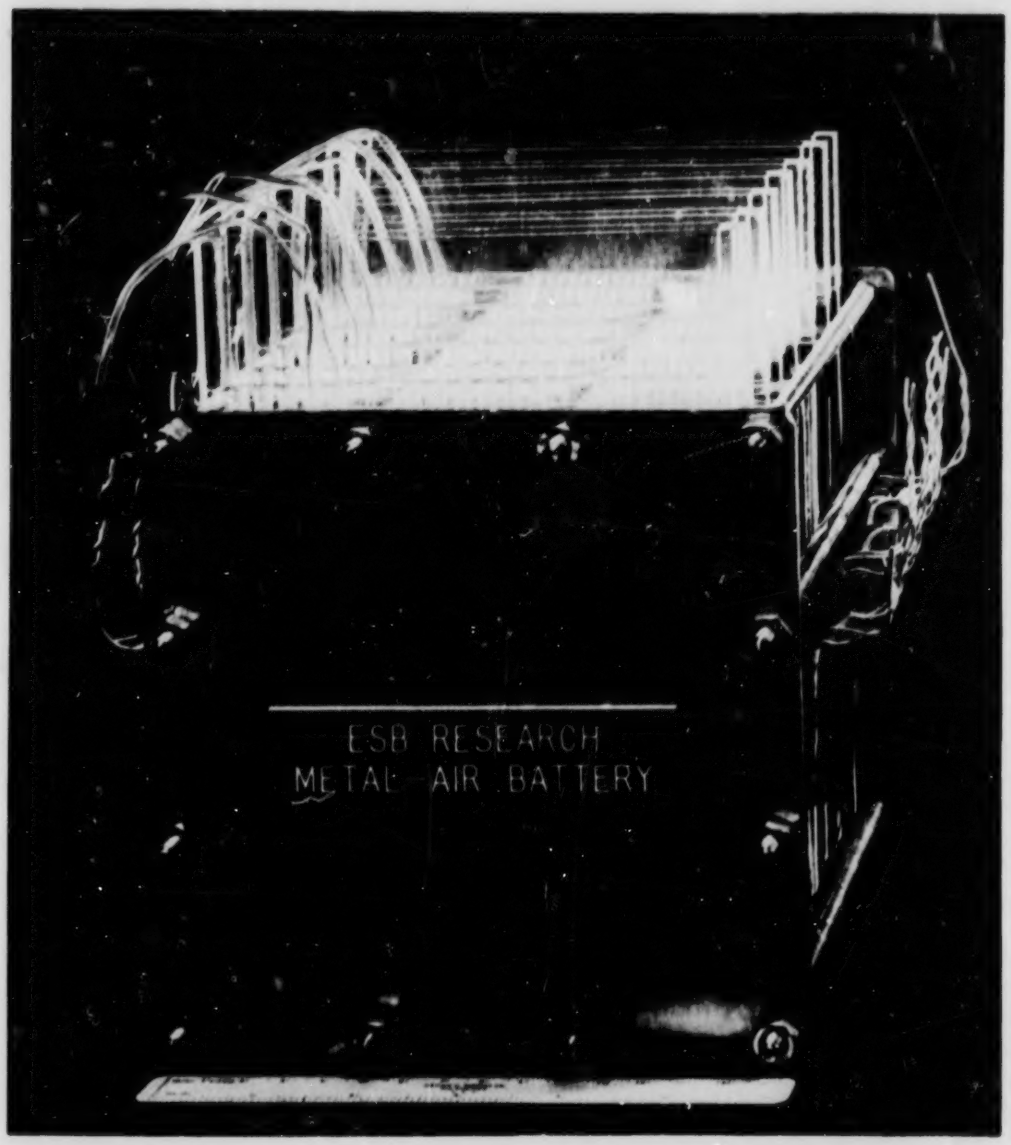

Figure 4. ESB research metal-air cell.

Figure 7 shows the cycle life performance of zinc-air cells of the present design, indicating good performance for over 50 cycles. We believe that the loss of performance is associated with the zinc electrode. In half-cell tests, the air electrode has given continuous performance equivalent to over 120,000 miles at 30 mph. Indicated energy density for the zinc-air system is in the range of 50 watt-hours per pound. Although recent discoveries show promise for improving the cycle life of the zinc electrode, many more improvements in separators and zinc electrode rechargeability will be required to make this system practical.

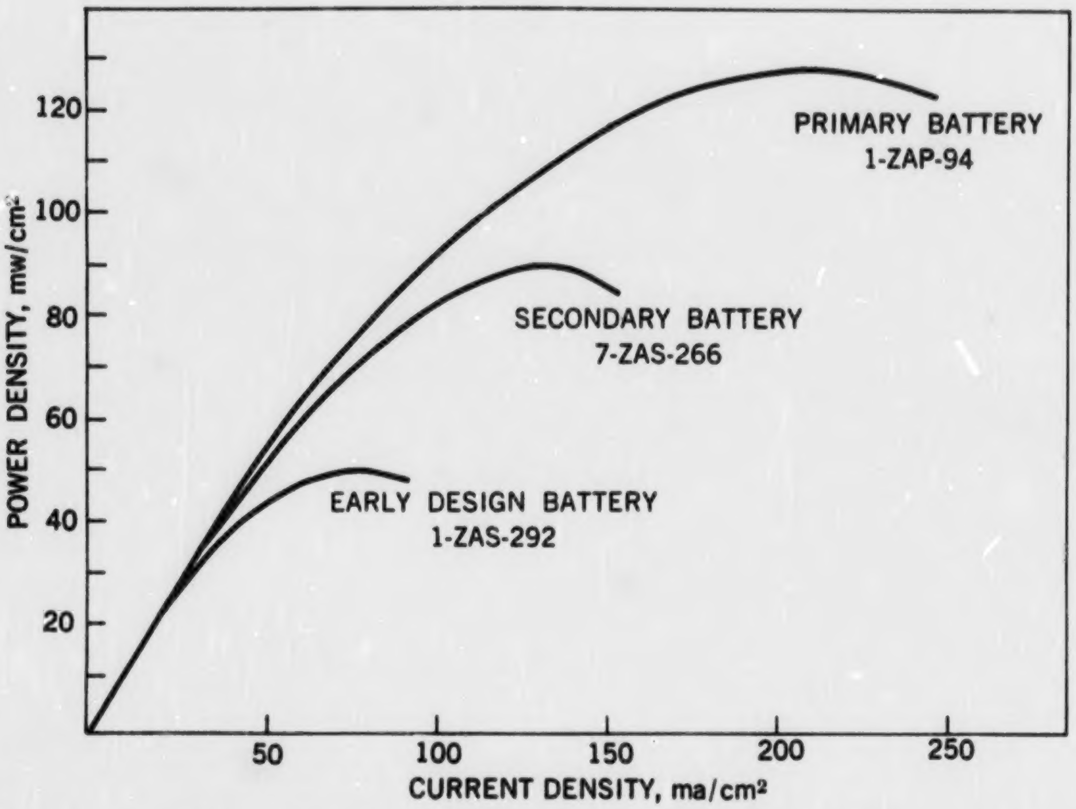

Figure 5. Power Output of Zinc-Air Cells.

Non-aqueous systems that use lithium or other alkali metals are intriguing because of the possibility of energy densities of over 100 watt-hours per pound. ESB Research has built cells with lithium anodes that delivered more than 100 watt-hours per pound at low discharge rates. Although these systems are capable of high energy densities, the low conductivity of the electrolytes makes the power densities rather low. Considerable improvements in rate capability will be required to make these systems attractive for vehicle applications.

Systems that use organic compounds as active materials have intrigued battery investigators for a number of years. Our recent investigation of certain organic compounds indicates good rechargeability and an energy density of over 50 watt-hours per pound of cathode in small laboratory cells. These systems show promise for high-rate rechargeable batteries, but will require more development. At present, the economics are uncertain.

Let me summarize our experiences. We believe it is feasible to construct delivery and small personal electric vehicles that will eliminate air pollution and satisfy a need for transportation over a range of approximately 50 miles. This can be done with existing commercial batteries. For much greater ranges, newer power systems will be required.

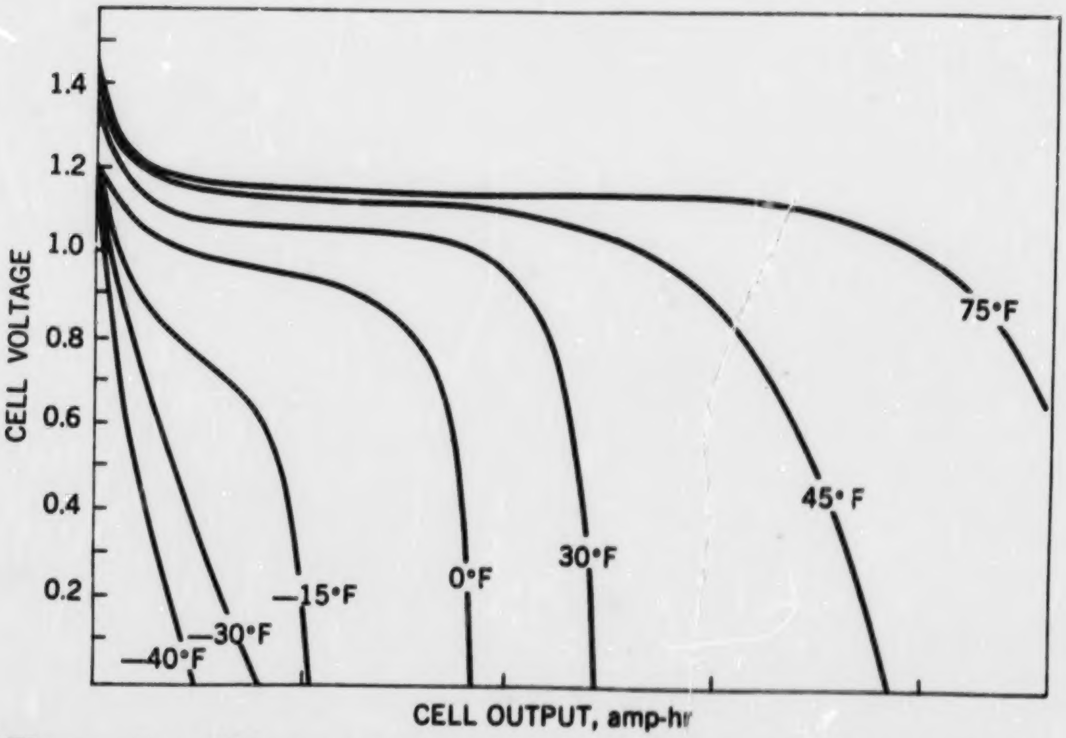

Figure 6. Effect of temperature on performance of zinc-air cell (1-ZAP-97, 4-hour rate).

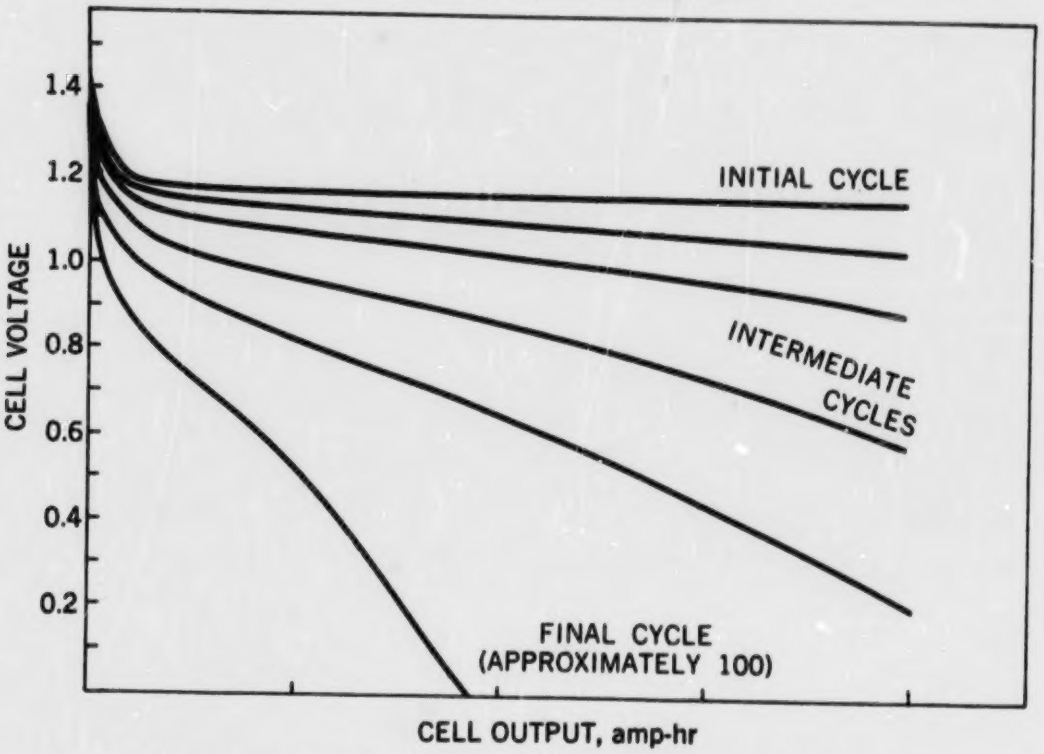

Figure 7. Typical cycling performance of zinc-air secondary cells (4-hour rate).

POWER SYSTEMS FOR ELECTRIC VEHICLES FOR MILITARY AND COMMERCIAL USE

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INTRODUCTION

Many power sources and many combinations of power sources have been proposed as the power plant for electric vehicular propulsion. In a recent report to the CTAB Panel of the U.S. Department of Commerce on Electrically Propelled Vehicles, the U. S. Army Engineering Research and Development Laboratories (USAERDL) reported for the U. S. Department of Defense (DOD) on the DOD program in electrical propulsion. It was pointed out that the types and severity of problems and the areas of emphasis for military vehicles were quite divergent from those for private vehicles, but that the basic technology being developed would, in most instances, be applicable to all electric propulsion programs.

The following are some of the conclusions presented in that report·

1. An all-battery power plant is not feasible for military vehicles because the charging facilities cannot be provisioned in a military environment.
2. The most promising power plants were gas turbines, fuel cells, and hybrid systems. State of the art and improvement potentials were considered when determining the applicability of these power plants.
3. The prime mover portion of a hybrid power plant where batteries are a part of the hybrid system should have the peak power capability. For operational characteristics required by military vehicles, it appears that dependence upon energy storage for peak power is not practical whereas it may be for commercial or private vehicles.
4. The three primary hybrid systems that can be considered are (1) gas turbine and fuel cell, (2) gas turbine and battery, and (3) fuel cell and battery.

Battery and fuel cell hybrids have been proposed and prototypes constructed for continuous duty power plants to meet the following objectives: (1) relatively low weight, (2) fuel economy, (3) silence, and (4) low pollution.

In the analysis of this hybrid, however, the most important considerations are weight and fuel consumption. For instance, if weight alone were the only consideration, turboalternators in the capacity of prime movers or peaking devices can be installed at

2.5 to 4.0 pounds per kilowatt. Batteries or fuel cells either alone or hybrided cannot approach this weight, but in noise or pollution or part load fuel consumption, the turboalternator may fail to meet requirements. If fuel consumption alone is important, a fuel cell is the most efficient energy conversion device available, but heavy. Because of the interest in air pollution reduction, the gas turbine is deleted from this discussion, although for military purposes the gas turbine or gas turbine hybrids look extremely attractive. This discussion, therefore, will be concerned with the two remaining power sources: (1) fuel cells and (2) fuel cell and battery hybrids.

FUEL CELL SYSTEM ANALYSIS

There are nearly as many different types of fuel cell systems as batteries. In fact, a fuel cell system itself may be a hybrid with more than one fuel conditioner or with hydrogen storage capabilities for peak power demands. To meet military requirements the fuel cell systems must use a logistically available liquid hydrocarbon fuel such as Compression Ignition—Turbine Engine (CITE) fuel or JP-4. This fuel is converted to a hydrogen rich stream for use in the fuel cell. Ambient air is the oxident in all cases.

Fuel cell systems operating on logistic fuels have been researched at USAERDL for more than a decade, and continue to be the most attractive energy conversion device for future general purpose stationary power plant use. A fuel cell system that is attractive for ground power may not, however, be attractive for vehicular use, since it would have been optimized for silence, fuel economy, and ruggedness, whereas for vehicular use it must be optimized for weight as well. As an analytical tool to aid in the optimization of fuel cell and hybrid systems, a Figure of Merit equal to:

$$\frac{\text{Power (kw)} - \dfrac{\text{Power plant weight (lb)}}{\text{100 lb/kw}}}{\text{Fuel consumption (kw/hr)}}$$

was used as measure of efficiency to indicate the power available to move the vehicle and payload, minus the power required to move the power plant. The 100-pounds-per-kilowatt constant is representative of the power-to-weight ratio of military vehicles now being designed.

The type of hydrocarbon-air fuel cell system with the highest Figure of Merit at the 40- to 100-kilowatt power level required by most military vehicles was an acid electrolyte, hydrogen-air fuel cell. Three types of fuel converters to change the liquid fuel to hydrogen were analyzed:

1. A steam reformer with the unpurified reformate passed directly to the fuel cell.
2. A partial oxidation unit with product gas passed directly to the cell.

3. A steam reformer—partial oxidizer combination with the partial oxidizer used for peak loads and transient operation. Schematics for each of these systems are shown in Figure 1. The weights for 40-kilowatt output, with modest state of the art improvements are shown in Figure 2 as a function of the fuel cell current density. (No frame or structural weight was charged to the power plant, however, since it was assumed the fuel cell would be built into the vehicle either using or contributing to its structural frame). Also shown in Figure 2 is the specific fuel consumption for the power plants with a spent fuel exhaust containing 10 percent hydrogen by volume.

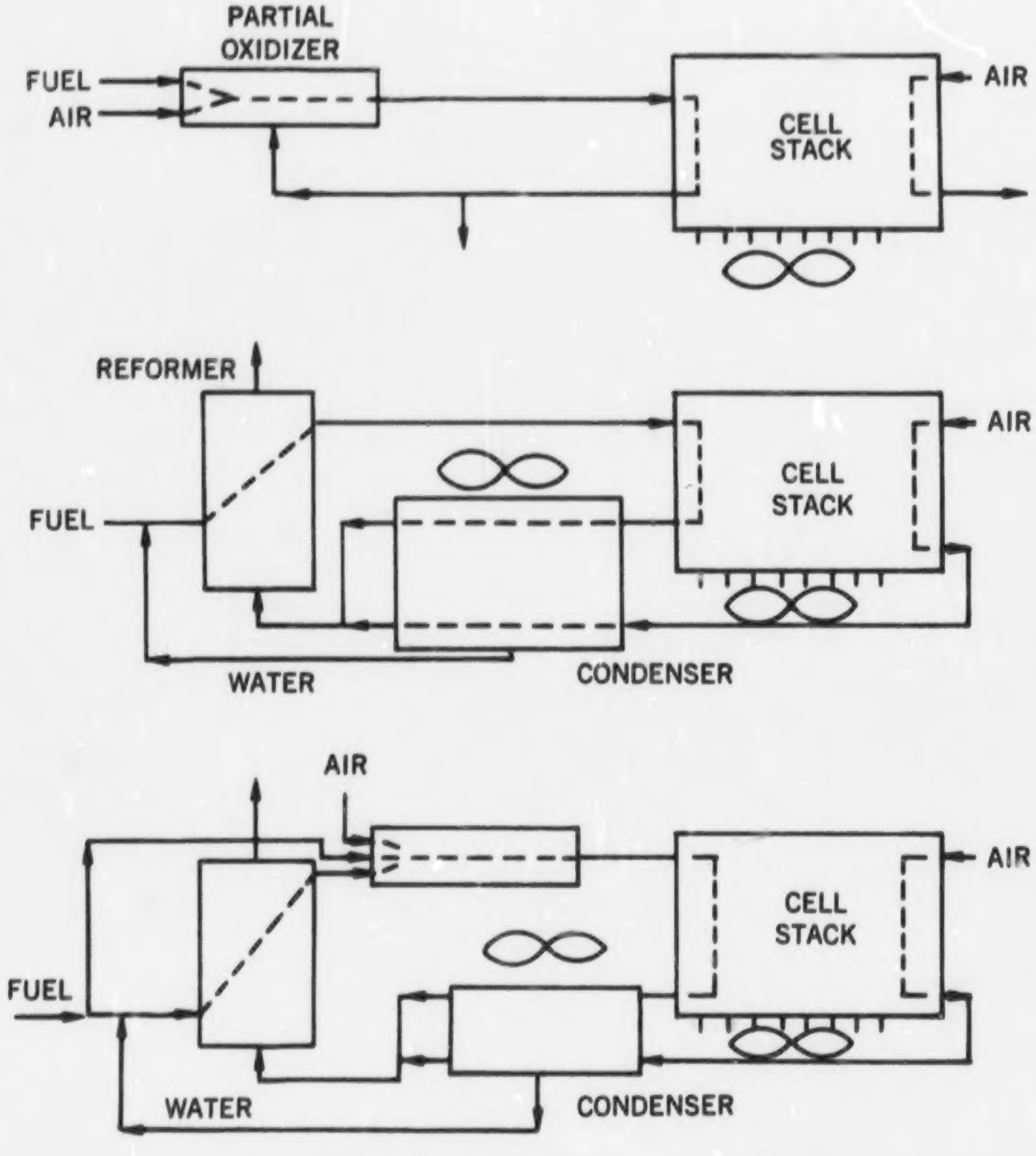
PARTIAL OXIDIZER
FUEL
AIR
AIR
CELL STACK
REFORMER
FUEL
AIR
CELL STACK
WATER
CONDENSER
AIR
AIR
CELL STACK
FUEL
WATER
CONDENSER

Figure 1. Fuel cell system schematics

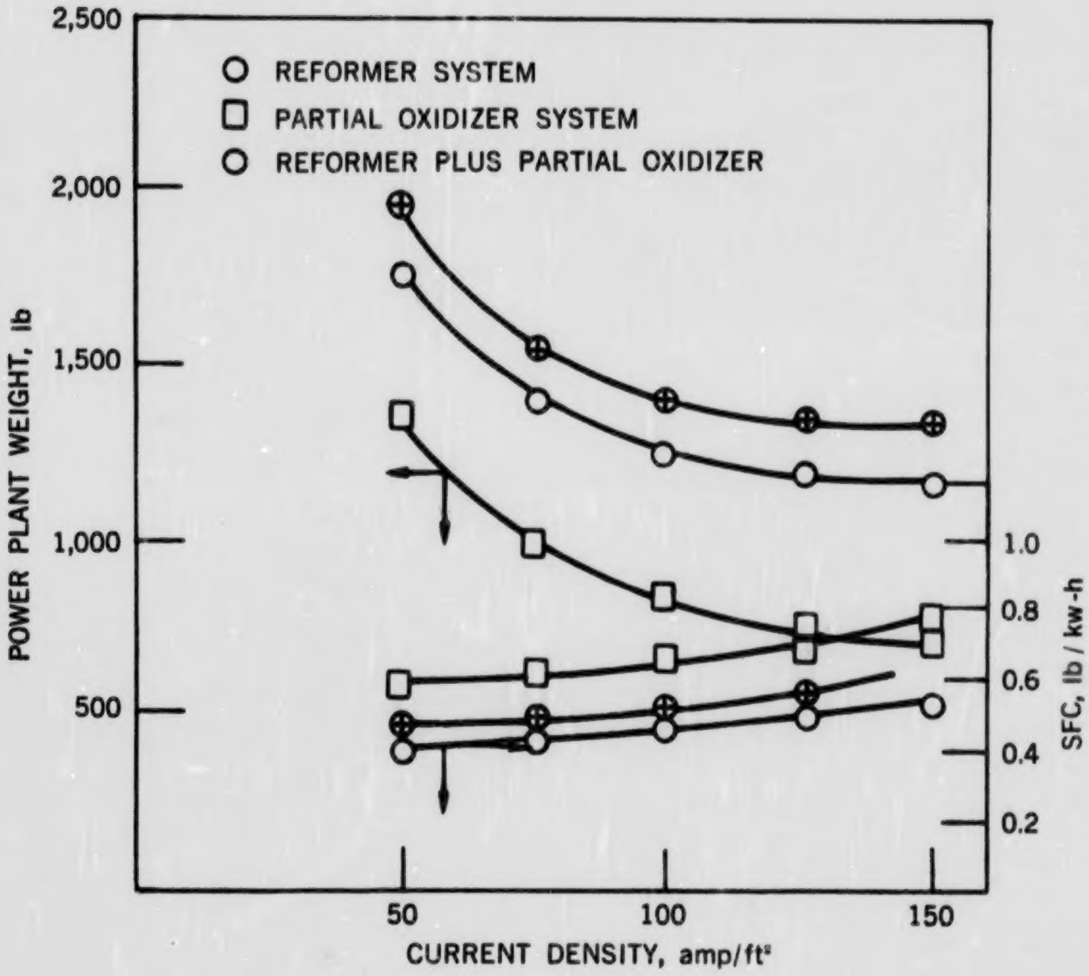

Figure 2. Forty-kilowatt indirect fuel cell power plant weights and specific fuel consumptions.

It can be see in Figure 2 that the reformer system is nearly twice the weight of the partial oxidation system, but uses only three-quarters of the fuel. When the Figure of Merit is applied to the systems as shown in Figure 3, the reformer and partial oxidizer systems are nearly equal, 0.2. By comparison, the Figure of Merit for the 94-horsepower spark ignition engine of an M37 truck is 0.095 at maximum power. For most commercial or private vehicles, 100 pounds per kilowatt will not give adequate performance. If the weight-to-power ratio of modern compact automobile (25 to 40 lb/kw) is substituted, the partial oxidizer and fuel cell combination is far superior to the other two systems.

In Figure 3, the systems all show a maximum at 85 amperes per square foot, but the fuel cell at this current density is far from its peak power, and additional ancillary devices can be installed to allow the cell to operate continuously at peak power. Figure 4 shows the Figure of Merit over the full range of power, with average or most economical power still at 40 kilowatts, but peak power between 64 and 70 kilowatts. For the partial oxidation system, the maximum specific power density of 66 watts per pound occurs close to the peak power point.

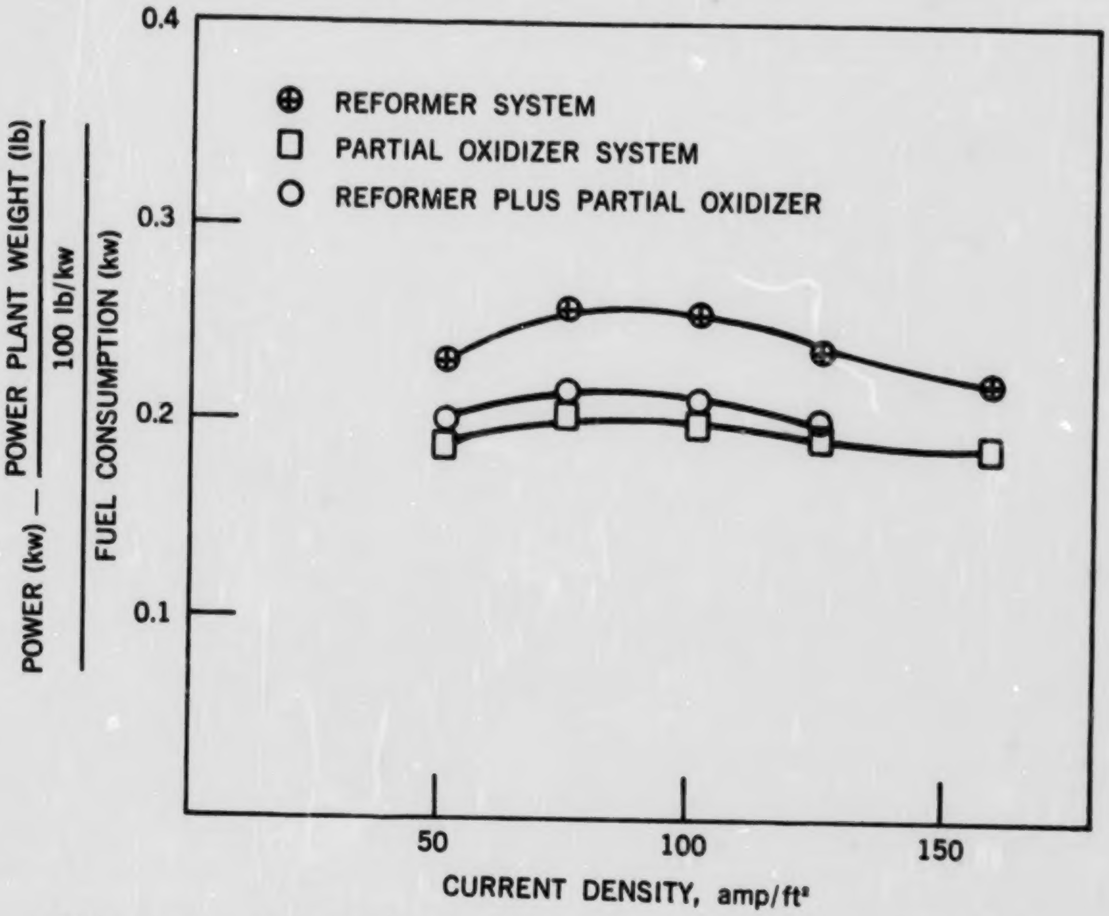

Figure 3. Forty-kilowatt fuel cell power plant figure of merit versus current density.

POWER SYSTEM ANALYSIS

Two battery systems were analyzed for use in the hybrid system. The first is an idealized 100-watt-hour-per-pound battery with unlimited charge or discharge rates and a 75 percent wattage efficiency over one cycle. This represents the goals for vehicular batteries needed for the hybrid system calculations. The second battery analyzed is an idealized metal-air type, limited on charge and discharge rates by air electrode performance only and limited on total charge by a maximum active metal weight. This battery discharges between 1.27 and 1.0 volt and charges between 1.9 and

2.23 volts, depending on ampere rate. Other goals for vehicular batteries that are important but do not enter into the calculations are (1) charge rates equal to discharge rates, (2) cycle life of over 10,000 cycles, (3) minimum of 50 percent of energy delivered at 80 percent of open-circuit voltage or higher, (4) self-discharge of less than 5 percent per day, and (5) 18-month activated life.

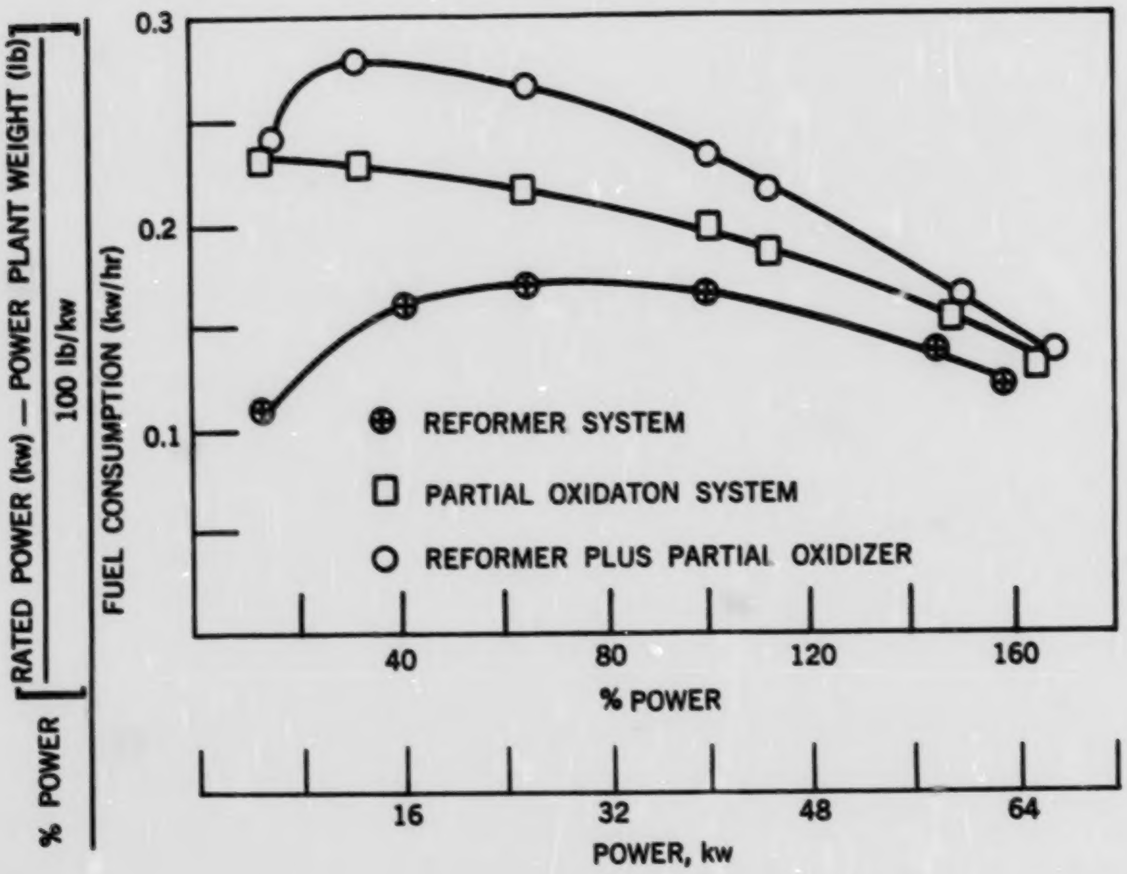

Figure 4. Fuel cell power plant figure of merit for 10 to 170 percent of rated power.

HYBRID SYSTEM ANALYSIS

A fixed-weight power plant was used for the hybrid analysis with the battery comprising 0 to 100 percent of the weight. Figure 5 shows the peak power per pound of power plant capability as a function of time for various fuel cell and battery combinations, with the ideal 100-watt-hour-per-pound battery. Also plotted is the recharge time of the battery when the power plant is providing less than peak power. For example, 200 watts per pound can be provided for 4 minutes by a 10 percent battery hybrid system. The recharge time with no net power out (all of the fuel cell power recharging the battery) is about 14 minutes. But if 40 watts continuous power is used by the vehicle (i.e. cruise power), it requires 40 minutes to recharge the battery, since there is little excess fuel cell power for charging. If the battery proportion increases to 50 percent, 200 watts per pound is available for a longer time, about 18 minutes, but since the fuel cell is much smaller, 33 watts capability, the recharge time at idle is over 2 hours and the system cannot sustain 40 watts per pound continuously.

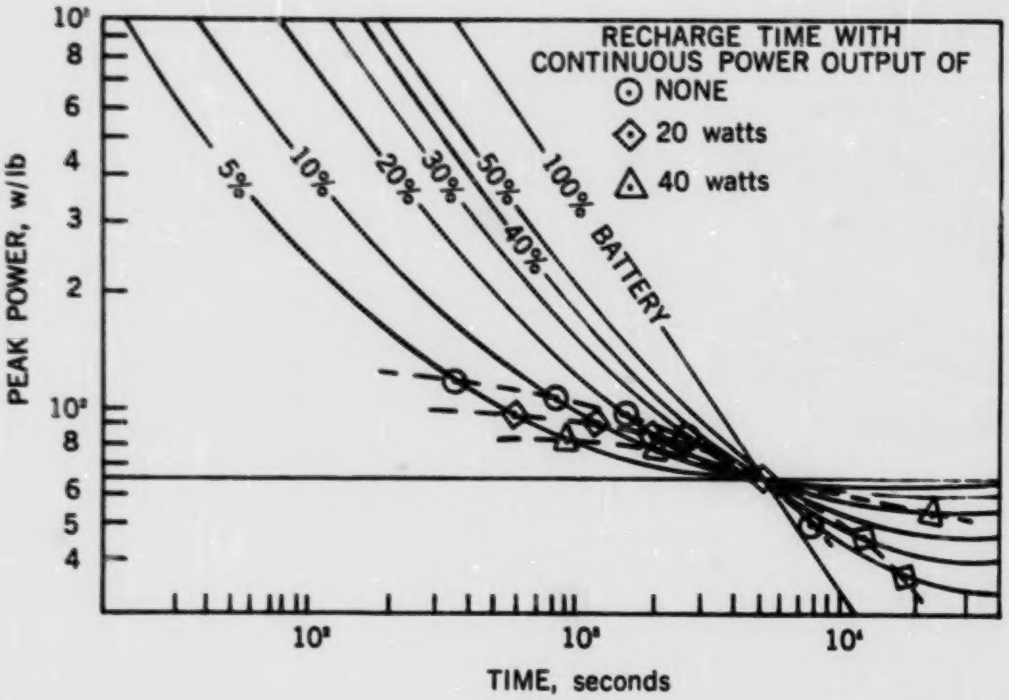

Figure 5. Ideal battery and fuel cell hybrid system peak power, discharge time, and recharge time.

Figure 6 shows much the same peak-power-versus-time capability for the metal-air battery, but anode and cathode limitations are apparent. Figure 7 shows the ratio of charge to discharge times as a function of continuous power required in watts per pound.

The minimum-weight hybrid system was calculated for two types of duty cycles. All of the duty cycles assume a peak power period, a continuous power period, and an idle period, with the battery fully recharged at the end of the cycle. Duty cycles 1 and 2 are short-term "milk-route" types of cycles, characterized by short peak power times. Duty cycle number 3 is a military battlefield power profile recently reported, and duty cycle number 4 is a USAERDL estimate of an 8-hour military mission based on proving ground tests on the fuel-cell-powered M37 truck. Table 1 shows the characteristics of the duty cycles and the operating characteristics of a hybrid system containing the idealized 100-watt-hour-per-pound battery. The hybrids listed under each duty cycle have the maximum performance possible under the peak-to-average-power ratios and time ratios dictated by the duty cycles. As would be expected, the "milk-route" duty cycles, 1 and 2, have superior power plant characteristics, both in peak power density and in continuous power capabilities. The minimum-weight hybrid for the military vehicle duty cycles has much poorer performance, especially in continuous power capability, which may be considered as the reserve or emergency power. Figure 8 shows the horsepower requirements for three classes of military vehicles, with the peak power requirement occurring over a wide range of conditions. It is not inconceivable that the peak power

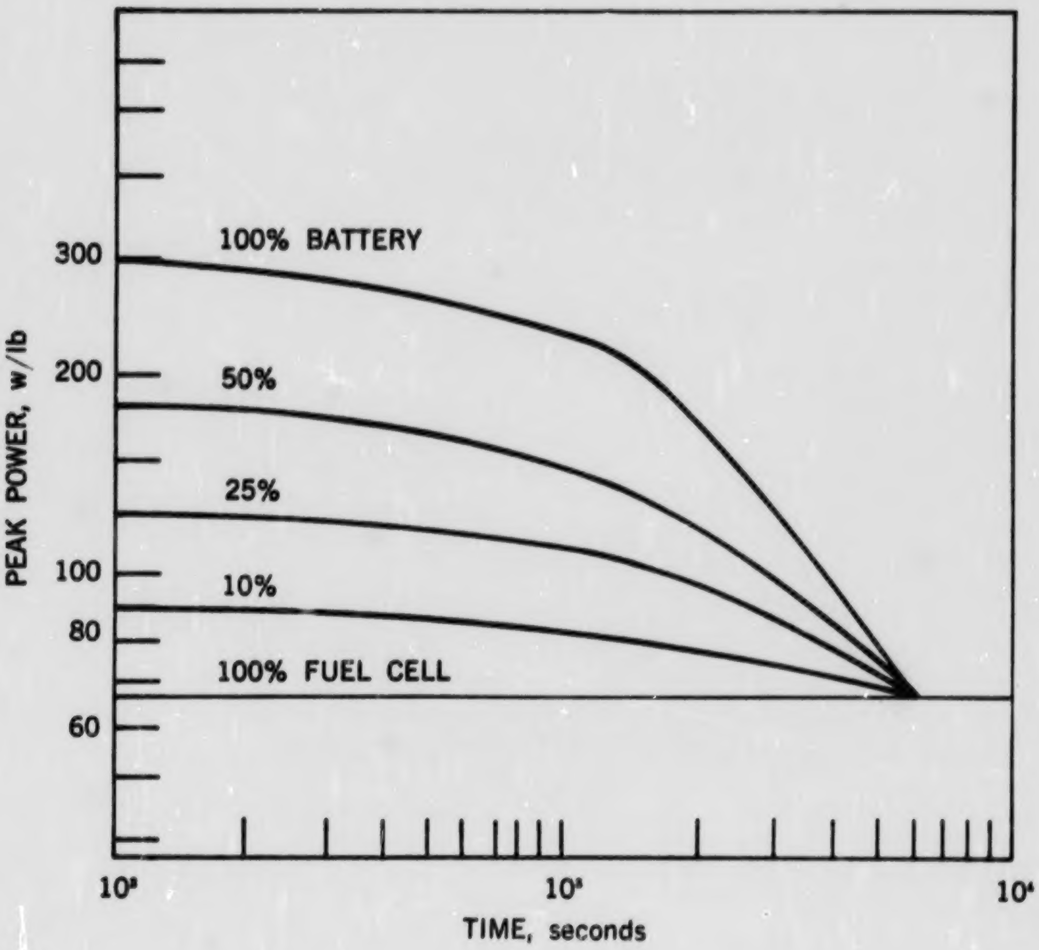

Figure 6. Metal-air fuel cell hybrid system peak power versus peak power time.

may be demanded for more than 1 hour continuously, especially since these are rough terrain vehicles with up to a 60 percent grade requirement. If the power plant is designed for duty cycle number 3, once the peak power demand has exceeded 1.2 hours, or if a series of short peak power bursts total this time without a substantial idle time, the available power drops to about 20 percent of peak. This is not sufficient power to maintain convoy speeds on level ground, much less on 3 percent grades.

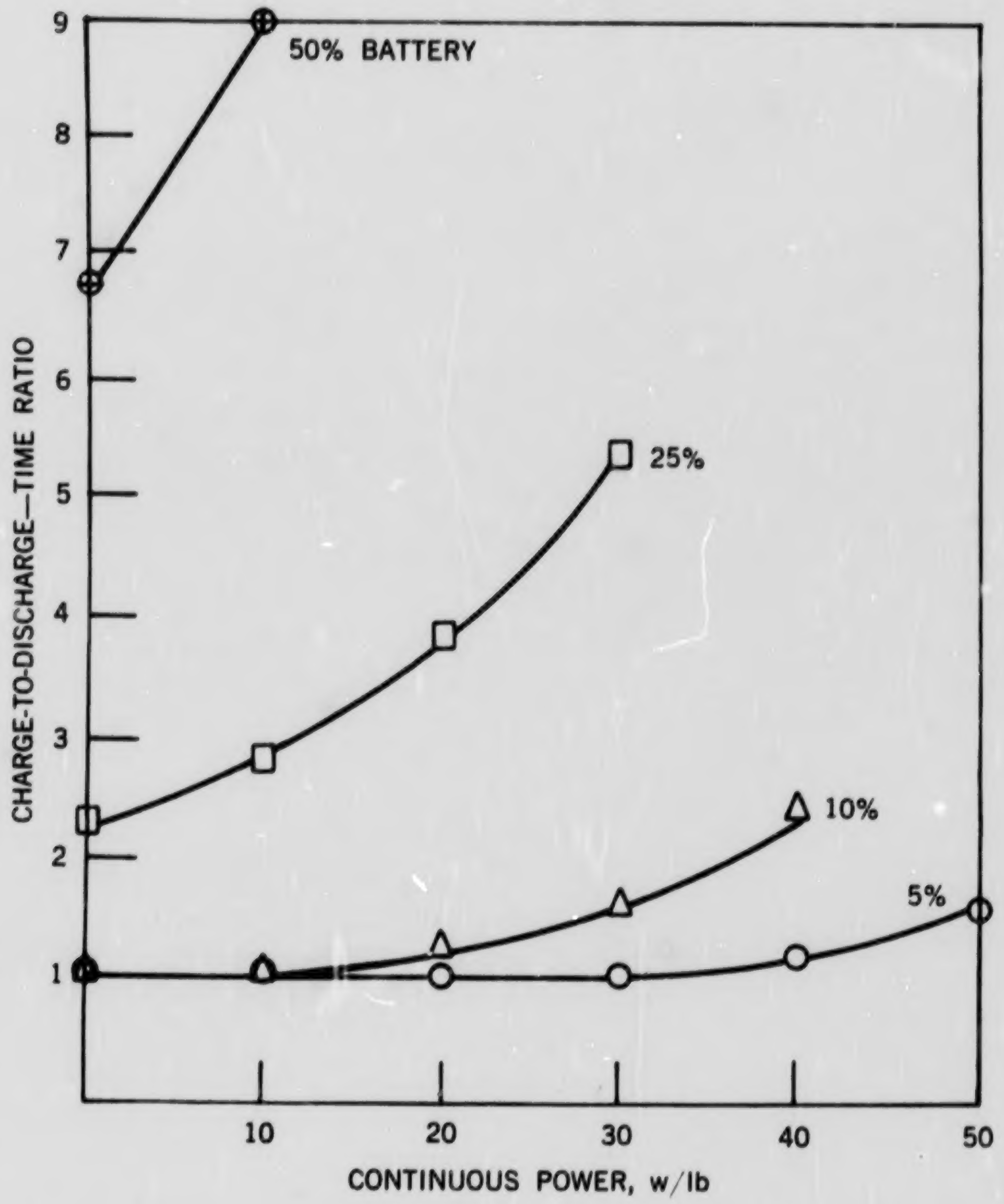

Figure 7. Metal-air battery and fuel cell hybrid charge-to-discharge-time ratio versus continuous power

Table 1. DUTY CYCLES AND OPERATING CHARACTERISTICS OF HYBRID SYSTEM CONTAINING IDEALIZED BATTERY (battery, 100 w-hr/lb)

Hybrid power plants characteristics	Duty cycle number 1	2	3	4
Duty cycle characteristics				
Peak power (Pt)	1	1	1	1
Peak power time (tp)	½ min	½ min.	1.2 hr	1 hr
Average power (Pa)	0.5 Pt	0.25 Pt	0.2 Pt	0.4 Pt
Average power time (ta)	3 min	3 min	15.6 hr	4 hr
Idle time (ti)	3 min	3 min	7.2 hr	3 hr
Hybrid operating characteristics				
Peak power density, w/lb	187	300	80	85
Continuous power, as % Pt	35	22	19	35
Continuous power, w/lb	65	65	15.5	30
Figure of Merit	0.178	0.185	0.176	0.179

Table 2 shows the same duty cycles and power plant performance as above. However, it augments the first in that the hybrid characteristics have been calculated for both types of batteries, and a comparison of an all-fuel-cell power plant with a hybrid power plant has been added. The specific fuel consumptions and Figures of Merit shown are better for the fuel cell power plants than the hybrids in all cases. The higher fuel consumption for hybrid systems and its consequent effect on the Figure of Merit due to the inefficiency of the battery in that from 35 to 100 percent more energy has to be put into a battery than can be taken out. Also, in a hybrid system a relatively small fuel cell works at full power continuously, either helping power the vehicle or charging the battery. Little advantage can be taken of the fuel cell's ability to operate with higher efficiency at part load.

For duty cycles 1 and 2, substantial savings of power plant weight are possible with the hybrid systems. The all-fuel-cell power plant weighs from 2 to 4.5 times the hybrid systems weight. For military duty cycles this weight savings is not substantial. An increase of less than 25 percent in power plant weight for either duty cycle 3 or 4 and all fuel cell power, the vehicle will not be restricted by peak power times. If the weight of fuel required for the mission is added, the weight differential drops to under 12 percent. The continuous peak power capability seems well worth the extra weight.

SUMMARY

Battery and fuel cell hybrid power plants do not offer appreciable savings in weight over fuel cell power plants for use in military vehicles. All-fuel-cell power plants offer the advantages of much lower fuel consumption, and more important, continuous peak power capability. Conversely, fuel cell and battery hybrid systems do offer the potential of a lightweight power plant for electrically powered commercial vehicles. For the military vehicle that may require extended periods of operation at high power levels and where noise or air pollution are not handicaps, hybrid systems utilizing engines as well as electrochemical power plants may be more suitable.

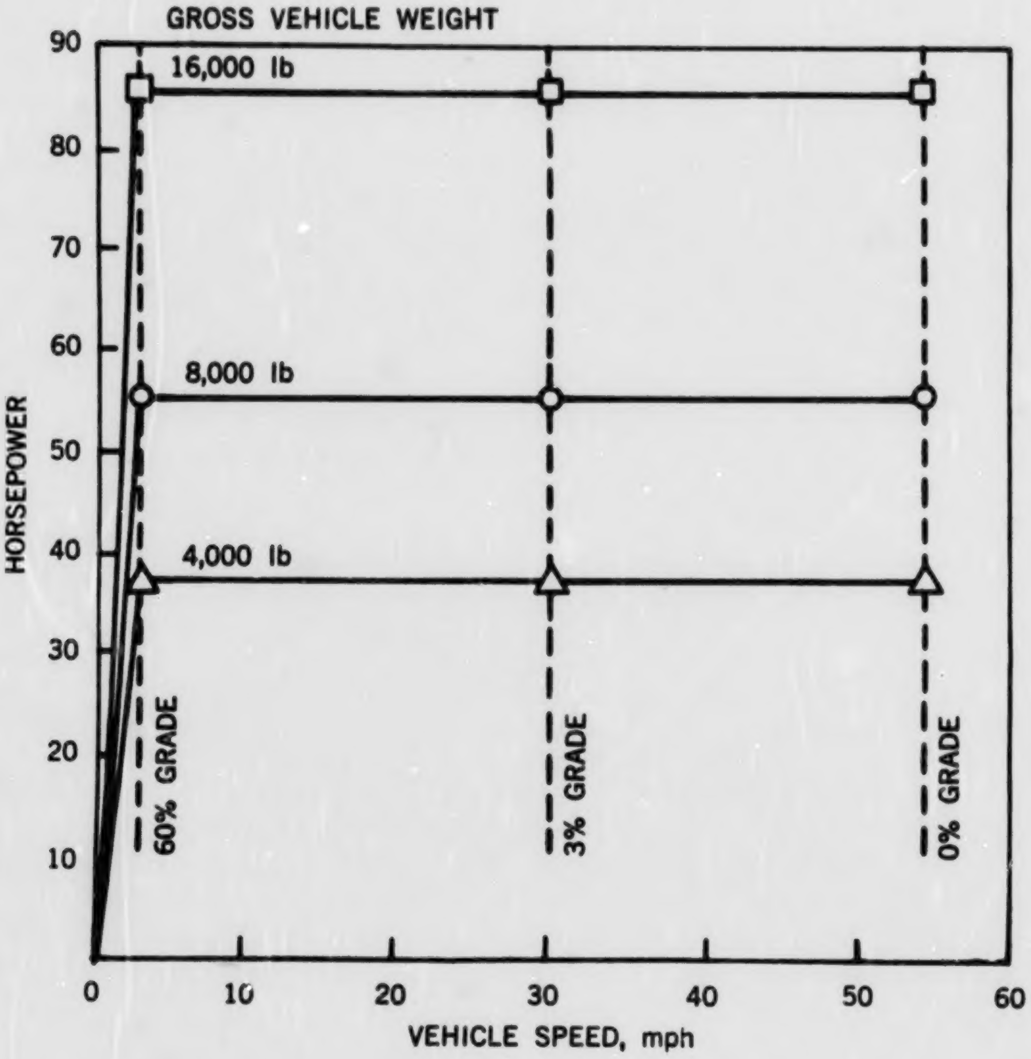

Figure 8. Vehicle horsepower requirements as a function of speed and slope.

Table 2. COMPARISON OF ALL-FUEL-CELL POWER PLANT AND HYBRID POWER PLANT

Hybrid power plants characteristics	Ideal battery (100 w-hr/lb)				Advanced metal-air battery (107 w-hr/lb at 1-hr rate)			
	Duty Cycle Number				Duty Cycle Number			
	1	2	3	4	1	2	3	4
Duty cycle characteristics								
Peak power, (Pt)	1	1	1	1	1	1	1	1
Peak power time, (tp)	½ min	½ min	1.2 hr	1 hr	½ min	½ min	1.2 hr	1 hr
Average Power, (Pa)	0.5 Pt	0.25 Pt	0.2 Pt	0.4 Pt	0.5 Pt	0.25 Pt	0.2 Pt	0.4 Pt
Average power time, (ta)	3 min	3 min	15.6 hr	4 hr	3 min	3 min	15.6 hr	4 hr
Idle time, (ti)	3 min	3 min	7.2 hr	3 hr	3 min	3 min	7.2 hr	3 hr
Hybrid operating characteristics								
Peak power density, w/lb	187	300.	80	85	133	162	83	80
Continuous power, as % Pt	35	22	19	35	36	24.5	22	43
Continuous power, w/lb	65	65	15.5	30	48	40	18	34.5
Battery only time at Pa	1.5 min	1 min	4.8 hr	1.6 hr	1.2 min	1.8 min	4.7 hr	1.7 hr
Specific fuel consumption, lb/kw-h	0.874	0.860	0.820	0.812	0.914	0.982	0.813	0.840
Figue of Merit	0.178	0.185	0.176	0.179	0.166	0.157	0.178	0.171
All-fuel-cell power plant								
Relative wt., fuel cell/hybrid	2.76	4.5	1.19	1.27	1.99	2.43	1.24	1.19
Specific fuel consumption, lb/kw-h	0.625	0.622	0.534	0.640	0.625	0.622	0.534	0.640
Figure of merit	0.224	0.225	0.262	0.218	0.224	0.225	0.262	0.218

FUEL CELL — BATTERY POWER SOURCES FOR ELECTRIC CARS

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In recent approaches to the electric automobile, attempts have been made to redesign vehicles to make them more appropriate to electric-drive concepts; to rethink the way in which people use vehicles so that an electric car may fit into a new type of transportation mode. All of the thinking is dominated by the fact that the electrical automobile cannot have all the versatility, range, speed, and other characteristics associated with present internal-combustion-driven vehicles. These considerations come back to basic limitations of the battery, which must contain the stored electrical energy required for the complete duty period.

BATTERY PROBLEM

The basic limitations a power source places on a vehicle are (1) the limited range or the number of miles the vehicle can travel without refueling, (2) the acceleration characteristics of the vehicle, and (3) the percentage of time the vehicle is available for its prescribed duty. For the conventional internal combustion engine the range depends upon the amount of gasoline carried, which is commonly adequate for about 300 miles, and the acceleration is dependent upon the design horsepower of the engine, which in most American cars is adequate to allow high-speed passing. The off-duty time for a conventional petroleum refueled vehicle is the 5- to 10-minute period required every 250 to 300 miles to refuel the gasoline tank.

For a vehicle battery, the range is limited by the energy density (kw-h/lb) of the battery; the acceleration is limited by the power density (maximum kw) of the battery; and the off-duty time is, of course, the time required to recharge the battery for the next discharge period. Conventional batteries that have been used, such as the lead-acid, nickel-iron, or nickel-cadmium, and in some experimental cases silver-zinc, all have distinct limitations in these three areas and also have the additional limitation of higher cost than those presently associated with the power source in a conventional vehicle.

Several new battery systems under investigation would significantly increase the energy density of future vehicle batteries. Based on the recent development of highly advanced fuel cell air cathodes, new zinc-air systems have become possible with conventional alkaline electrolytes. They are, however, limited to about 80 watt-hours per pound. There are some difficulties in achieving very high rates without drastically affecting the energy density, and long life recharge capability is still highly uncertain. Investigators have explored two types of nonaqueous electrolytes. The first consists of salts dissolved in organic electrolytes used with alkali metal anodes and halogen cathode materials. These have been extensively investigated by National Aeronautics and Space Administration for satellite communication batteries, but do not appear attractive for vehicle propulsion because of the very low rates that are obtained and the many problems involved with the dissipation of heat generated by the inefficiency of the reactions. The second major category of non-aqueous systems includes the molten electrode or molten electrolyte types. The sodium-sulfur battery announced to the public by Ford Motor Company only last month is an example of this type of cell. The lithium-chlorine batteries being developed by General Motors use a molten lithium anode, lithium chloride electrolyte, and a porous carbon cathode in which chlorine gas is either evolved during recharge or consumed during the discharge. These systems based on sodium or lithium anodes and sulfur-, chlorine-, or possible fluorine-based cathode materials have theoretical energy densities sufficiently high that practical devices in the range of 150 to 200 watt-hours per pound are within the realm of feasibility. Together with Ford and General Motors, several other investigators are trying to tackle the problems associated with the containment of these reactive materials in configurations that can make them attractive as high-power-density, high-energy-density batteries. The concept of using a molten electrolyte battery operating at elevated temperatures introduces new types of operational patterns for vehicle propulsion. The whole question of start up and how one maintains the system in molten condition ready for operation over extended periods must be considered.

If one requires equivalent performance from any new electrically propelled vehicle, as is now obtained from conventional vehicles using internal combustion engines, the present performance parameters must be determined. The conventional power plant weight associated with typical vehicles is shown in column 2 of Table 1.

This includes just the engine weight. The weight of the transmission and the power train for this calculation were assumed to be equivalent to that required in the future for the electrical drive train system. Column 3 shows the fuel weight normally carried in these vehicles immediately after refueling. The total weight of the power plant, the fuel, and the tankage is shown in column 4. The amount of energy that can be generated from this fuel in the internal combustion engine converter is, of course, a function of the conversion and utilization efficiency. Based on detailed calculations, the specific fuel consumption for these vehicles during their normal duty cycle, which includes periods of idle, traveling across country, on secondary roads, on highways, and at peak power, has been calculated in terms of pounds of petroleum fuel per kilowatt-

Table 1. WEIGHT AND FUEL CONSUMPTION SUMMARY FOR CONVENTIONAL INTERNAL COMBUSTION POWER PLANTS

Vehicle Type	Conventional power-plant weight, lb	Fuel weight, lb	Total wt (PP, fuel, and tank), lb	Duty cycle SFC,[a] lb/kw-h	kw-h Equiv	w-hr/lb
¼ ton	418	108	555	2.10 (11%)	51	97
¾ ton	590	146	773	1.53 (12%)	95	129
2½ ton	1,550	305	1,932	1.02 (18%)	299	161
5 ton	1,675	476	2,270	0.97 (19%)	490	229
10 ton	2,200	1,036	3,447	1.02 (18%)	1,015	314
Tank	4,870	2,741	8,068	1.41 (13%)	1,940	254

[a] Specific fuel consumption.

hour and is shown in column 5. From these data the kilowatt-hour equivalent of the fuel, and the watt-hours per pound of total engine and fuel can be readily calculated. This represents the energy density of the power source in conventional vehicles. The watt-hours per pound range from approximately 100 for the one-quarter-ton truck to over 300 for the 10-ton cargo carrier. From this comparison it is obvious that no aqueous electrolyte battery, not even the 80 watt-hours per pound estimated for the zinc-air system, can directly replace the engine and fuel tank in conventional vehicles and give equivalent performance. If the molten battery systems could be developed to store 150 watt-hours per pound, they could be used as direct replacement for conventional engine power sources in all but the very heavy and long-range vehicles. Improved versions with energy densities of up to 300 watt-hours per pound would be required for the larger trucks and combat tanks.

Table 2 shows the power requirements, in kilowatts provided to the drive train, required during idle, cross country, secondary roads, highways, and at peak power.

Table 2. POWER REQUIREMENTS TO DRIVE TRAIN OF CONVENTIONAL VEHICLES
(in kilowatts)

Vehicle	Idle (30%)	Cross country (20%)	Secondary (20%)	Highway (25%)	Peak (5%)
¼ ton	—	2.4	4.5	6.3	37
¾ ton	—	5.6	9.4	12.2	55
2½ ton	—	11.5	19.9	24.0	108
5 ton	—	17.4	29.4	33.4	130
10 ton	—	61.3	97.5	104.0	216
Tank	—	153	261	—	400

Internal combustion engines have been designed on the basis of providing the peak power required and in many cases almost idle during normal operating conditions for highway transit. To give equivalent performance the battery must of course be capable of providing the same output. These discharge rates are no problem for the molten electrolyte batteries because of the very high conductivity of the electrolytes and because of the fast electrode reactions at these elevated temperatures. Most of these peak demands require discharge at about the 1-hour rate. Molten batteries are capable of high capacities and efficiencies even at 15- to 20-minute rates. The molten electrolyte systems, therefore, have sufficient power density for these vehicle applications.

The third major limitation of battery systems is the high percentage of nonduty time during which the battery must be recharged. Various proponents of the family-type electric car have suggested the overnight recharge to replace the electrical power consumed during the day's use. This immediately limits the type and extent of use of the electric automobile because it must stay within its 1-day range, often mentioned as a maximum of 150 miles, and can only be recharged at home or where other suitable charging equipment may be available. An alternative would be supplying energy to the electrical automobile by a method analogous to that now employed for refueling conventional hydrocarbon-burning vehicles. This requires a fast charge capability for the battery so that its energy content can be completely renewed in a period of approximately 10 to 15 minutes, which is only somewhat longer than now required for obtaining a full tank of gas at the gasoline service station. The kinetics of the electrode reactions of the molten electrolyte cells are sufficiently rapid so that charging of a total system within 15 minutes is a possible feasible solution. Special designs to minimize resistance in the electrodes and electrolytes must, of course, be taken and some loss of efficiency in recharge is inevitable. If high-power charging stations were available across the country, such as gasoline service stations are now, the total energy content for another 200- to 300-mile trip could be transferred to the molten electric battery in this short period of time. One of the principal problems is, however, the large amount of current that must be conducted through the cables that link the charging station to the battery. This represents a very significant bus bar weight on the vehicle. This extra weight in terms of cell terminals and conductor hardware is so large that it drastically reduces the effective watt-hours per pound of the battery. It is, therefore, highly unlikely that a 15-minute recharge battery can be achieved with the watt-hours per pound required for the vehicles listed in Table 1. At first glance the alternative appears to be either to reduce the range of the vehicle and to allow fast recharge so that an additional increment of power can be quickly taken on as required or to remain with the concept of overnight charging and increase the range of the vehicle by developing batteries with significantly higher watt-hours per pound.

FUEL CELLS

Fuel cells have also been proposed for vehicle propulsion. Except for the cases where very special fuels and oxidants such as tank hydrogen and tank oxygen have been utilized, very little progress has been made. The economics of electric vehicle propulsion does not lend any attractiveness to the utilization of special fuels such as hydrogen or hydrazine in fuel cells for vehicle propulsion. The cost of hydrocarbon fuels for utilization in hydrocarbon-air fuel cells for vehicle propulsion is, of course, extremely attractive, but the present day complexity and weight of hydrocarbon air systems make them infeasible for vehicle mounting. One principal problem is that a fuel cell is much like an internal combustion engine in that it must be sized to deliver the peak power demands. The peak requirements for the military vehicles shown in Table 2 would have to be used as the design point for the rated performance of the hydrocarbon-air fuel cells. At the present power density of the fuel cell (50 to 100 lb/kw), it is evident that the hydrocarbon-air fuel cell weight would be in excess of the total vehicle weight. Even though a fuel cell would have a high energy conversion efficiency (40 to 50%) at its rated power, which is the peak power requirement, as listed in Table 2, its energy conversion efficiency at normal cross country power requirements could be less than 10 percent and not much better than internal combustion engine efficiencies.

FUEL CELL — ENERGY STORAGE HYBRID SYSTEM

Molten electrolyte batteries have the advantage of high power density, easily providing the peak currents required for fast acceleration and for heavy service, but have limitations in the total amount of energy that can be stored in a given amount of weight They also have the disadvantage of often requiring longer periods for recharge or for short charge periods having significantly lower energy storage capacities. Fuel cells on the other hand have the advantage that they can convert a hydrocarbon fuel, which has an extremely high watt-hours per pound of theoretical energy, very efficiently into electrical energy, but have the difficulty of having very low overload capabilities, and therefore, have to be designed for the peak power requirements that are only utilized 5 percent of the total time during a day's operation. In the design of a future power source that is to be strictly limited to the weight of the existing engine (transmission and drive train excluded) and its normal amount of fuel, and that is to be optimized for lowest specific fuel consumption over its average daily duty cycle (optimum high efficiency) it is logical to choose a fuel cell and battery hybrid system. A hybrid power source system would consist of approximately an equal weight of hydrocarbon fuel, fuel to electrical converter, and battery. The one-third of the weight that is battery would store electrical power for use during peak requirements or where the power required is above the average. The one-third of the weight in the fuel to electrical converter could be a highly simplified liquid hydrocarbon fuel cell used as a battery charger running at an average power level for the entire daily duty cycle, with power being stored during idle or below-average demand periods for use during periods of above average drain.

The exact proportion of weight in the fuel cell battery charger and that in the battery must, of course, be dependent on the particular duty cycle of the vehicle, with the peak-to-average power ratio being the most important design parameter. Table 3 indicates the rated kilowatt capacity of the fuel cell and the kilowatt-hours of battery storage for the vehicles previously described.

Table 3. FUEL CELL CAPACITY AND BATTERY STORAGE REQUIRED FOR VARIOUS CONVENTIONAL VEHICLES

Vehicle	Rating, kw	Rating of fuel cell,[a] kw	Max. power from fuel cell, kw	Energy storage, kw-h
¼ ton	2.4/4.5/6.3/37	4.5	6.75	37
¾ ton	5.6/9.4/12.2/55	9	13.5	50
2½ ton	11.5/19.9/24.0/108	20	30	94
5 ton	17.4/29.4/33.4/130	30	45	102
10 ton	61.3/97.5/104.0/216	100	150	78
Tank	153.0/261.0/——/400	175	263	164

[a] Based on 0.8-volt single cell.

The fuel cell battery charger is given a nominal power rating corresponding to 0.8 volt per single cell and is capable of overrated operation up to the maximum kilowatts listed in the fourth column of Table 3. In each case, the secondary road and highway steady power demands can be satisfied by the fuel cell, with the battery being used only during peak power demands.

A typical system may use the molten electrolyte lithium-chlorine battery, which operates at 450° to 600°C together with a reformer and a molten carbonate matrix electrolyte fuel cell operating at the same temperature. Since excellent electrical transient response is provided by the storage battery energy, the lag time of the reformer and fuel cell can be rather lengthy, thus allowing very simple, largely self-regulating controls.

FUEL CELL AND BATTERY VEHICLE POWER SOURCE PERFORMANCE

In Table 4 the distribution of weight between fuel cell component, battery component, fuel, and fuel tankage is given for the vehicles.

Table 4. WEIGHT DISTRIBUTION OF FUEL CELL AND BATTERY VEHICLE POWER SOURCE

Weight of fuel cell, lb	Weight of battery, lb	Weight of fuel, lb	Weight of tank, lb	Total weight, lb	Duty cycle power source efficiency, %	Vehicle power utilization efficiency, %	Specific fuel consumption lb/kw-h	Equivalent kw-h	(24-hour) Days	W-hr/lb
155(4.5kw)	246	139	15	555	52	36	0.51	278	2.4	500
297(9kw)	334	128	14	773	52	36	0.51	256	1.2	332
630(20kw)	626	609	67	1,932	54	38	0.49	1,218	2.9	630
900(30kw)	680	621	69	2,270	54	38	0.49	1,242	2.1	550
1,785(70kw)	855	1,051	117	3,808	51	36	0.51	2,102	1.8	560
3,675(175kw)	1,094	2,969	330	8,068	48	34	0.54 (2,000 w-hr/lb)	5,938	2.0	735

Each hybrid system meets the duty cycle power requirements shown in Table 2 and has the equivalent weight of the conventional engine as given in Table 1. This means that the hybrid fuel cell and battery system postulated for each of these vehicles will be equivalent in every respect to the conventional internal combustion engine in performing the specific duty cycle. The calculations were made on the basis of sizing the fuel cell and battery according to Table 3 requirements and using all excess allowable weight for fuel. The power source efficiency was calculated during performance of the actual duty cycle and is shown in column 7 of Table 4. Columns 8 and 9 indicate the allover utilization efficiency and the specific fuel consumption based on an assumed 70 percent efficient drive train. Based on these efficiency caluculations, 2,000 watt-hours are obtained from every pound of fuel consumed. This gives a hybrid fuel cell and battery system for these vehicles an energy density of from 500 to 700 watt-hours per pound.

Table 5 summarizes the performances of the conventional internal combustion engine and the battery and fuel cell system.

Table 5. PERFORMANCE COMPARISON OF THE CONVENTIONAL INTERNAL COMBUSTION ENGINE AND THE BATTERY AND FUEL CELL HYBRID SYSTEM

	Conventional			Fuel cell — battery		
Vehicle Type	Efficiency, %	Days before refueling	W-hr/lb	Efficiency, %	Days before refueling	W-hr/lb
¼ ton	11	0.44	97	36	2.4	500
¾ ton	12	0.45	129	36	1.2	332
2½ ton	18	0.71	161	38	2.9	630
5 ton	19	0.84	229	38	2.1	550
Combat tank	13	0.64	254	34	2.0	735

Efficiencies of the battery and fuel cell system can be improved by a factor of 2 to 3, giving energy densities that would allow these vehicles to go three to five times as far before refuelings.

CONCLUSIONS

Through the use of a fuel cell and battery hybrid power source, all of the so-called vehicle "battery" problems can be overcome. This power source allows an electric vehicle to have:

1. Full-range capability.
2. Excellent acceleration characteristics.
3. Very fast energy refuel.

Achieving the performance outlined for the vehicle requires the successful development of a 150-watt-hour-per-pound molten electrolyte battery and a 20- to 35-pound-per kilowatt hydrocarbon fuel cell. Research progress indicates that these goals should be achieved in operational hardware within the next 5 to 10 years.

ELECTRIC VEHICLE RESEARCH

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Among the several types of automobiles presently being considered for electrification are small urban cars of limited range and acceleration performance, larger cars intended to be competitive with today's general purpose passenger vehicles, and special automotive vehicles such as taxi-cabs.* Hence considerable research and development effort is going into electrochemical energy systems.

Our effort in this area is focussed on two principal objectives: (1) to conduct exploratory research into a wide variety of promising electrochemical couples such as lithium-sulfur, lithium-air, sodium-chlorine, and sodium-sulfur and (2) to carry out research and development work on high-performance energy conversion systems based on the lithium-chlorine couple.

This latter objective is pinpointed here because our work to date under the first objective indicates that the lithium-chlorine couple holds the best promise for satisfying most of the applications of greatest interest to us. Table 1 explains one of the reasons why this is true. It gives the energy storage density of various reactant pairs in watt-hours per pound of reactant—that is, per pound of reactants that have to be carried in the automobile either before or after the battery has been discharged.

Table 1. COMPARISON OF THEORETICALLY AVAILABLE ENERGY FROM A VARIETY OF REACTANT PAIRS

Reactant pairs	Li/Cl	Li/S	Na/Cl	Na/S	Zn/Air	Li/Air	H_2O_2
Carried reactants, w-hr/lb	1,050	1,130	600	300-650	500	2,000	1,600

From the energy storage density standpoint, the lithium-chlorine couple looks good; the lithium-sulfur couple looks slightly better, the sodium-chlorine couple looks pretty good; and the lithium-air couple looks best of all. However, the presently achievable electrochemical reaction rates at the air electrode are not good even with the most expensive catalysts, and the direct lithium-air couple still suffers from that obstacle, so it remains at present an item of purely potential interest to us. In fact, our study of electrode reaction rates for these couples has caused us to look most favorably, as of now, on the lithium-chlorine couple. Figure 1 depicts a research-type electrochemical cell we have used to explore the performance potential and operating features of this couple.

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* Other types of vehicles that are already electrically powered or are being considered for electrification include light, medium, and heavy trucks; locomotives; and off-road vehicles such as dump trucks and scrapers.

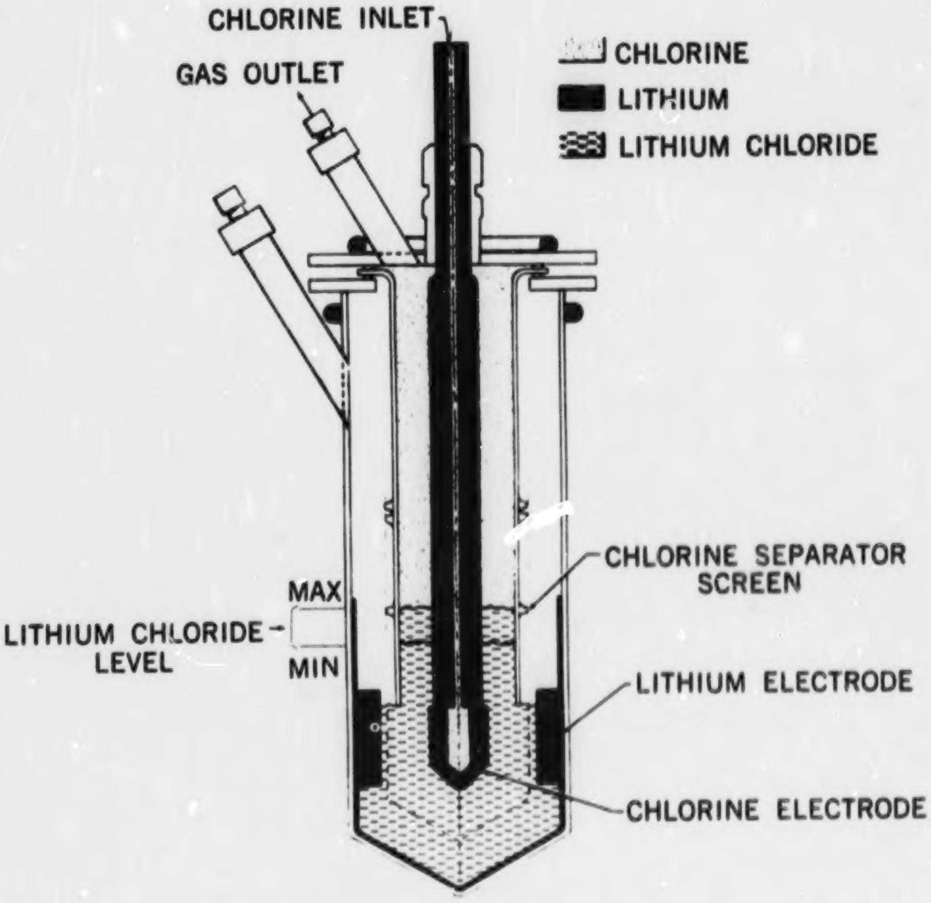

Figure 1. Vertical experimental lithium-chlorine cell.

The chlorine electrode, which is the positive pole of the cell, utilizes a porous carbon frit to separate the molten lithium chloride electrolyte on the one side from the hot chlorine gas on the other. The molten lithium chloride does not wet the carbon frit. The gaseous chlorine molecules are forced through the pores of the frit to the interface between the carbon and the lithium chloride. There they go into solution, at which time most of them dissociate, gain an electron from the carbon, and become negative ions in the melt. We have devoted considerable attention to the basic physical mechanisms underlying the operation of this electrode, and believe we have achieved an excellent understanding of its electrochemical behavior. Moreover, we have rather extensively studied its operating features from an engineering point of view, and believe that it poses no insurmountable problem to the future development of a very high-performance battery. Our tests have shown the feasibility of achieving chlorine electrode current densities up to 4,000 amperes per square foot without significant polarization losses, and still higher current densities are possible.

Similar studies have been accomplished on the lithium electrode, which is the negative pole of the cell. Here we use a porous, stainless steel structure to bring molten lithium from the one side to the molten lithium chloride on the other. The stainless steel is completely wetted by at least a thin film of molten lithium, so lithium chloride is excluded from touching it as long as some excess of lithium remains. Thus, the electrochemical reaction occurs on the surface of the thin film of molten lithium facing the lithium chloride. Our tests show that current densities achieved at this electrode can exceed 40,000 amperes per square foot without noticeable polarization losses. Hence, we believe that the lithium-chlorine electrochemical cell is potentially capable of very high-power-handling capacity, and, further, we suspect that this power-handling capacity is ultimately going to be limited more by the chlorine electrode than by the lithium electrode.

Most of our current research problems in connection with this system involve trying to find materials capable of long life while handling the highly corrosive hot chlorine gas, the molten lithium chloride, the molten lithium, and the corrosive impurities that may creep into the system. Our research is still in an early stage, and potential life data for a lithium-chlorine electrochemical power system cannot yet be presented.

On the basis of our work to date, we believe that development of a rechargeable electrochemical power system is technically feasible. In the 100 hp class with an energy storage capacity of about 100 hp-hours, we believe we can probably achieve a lithium-chlorine electrochemical power system with the characteristics listed in Table 2.

Table 2. CHARACTERISTICS OF LITHIUM-CHLORINE POWER SYSTEM

Open circuit voltage	3.5 volts per cell
Average operating voltage	3.2 volts per cell
Power capacity	0.2 hp per pound of electrochemical power system
Energy storage capacity	0.13 hp-hour per pound of electrochemical power system

As yet, however, we are far from being assured that we can solve our problems of long operating life, operating hazards, and a favorable first-cost picture.

Recently General Motors described and demonstrated two full-scale electric vehicles and showed that there are currently no absolute technological barriers to such developments (Rishavy, Bond, and Zechin, 1967; Marks, Rishavy, and Wyczalek, 1967; Agarwal, 1967; Wyczalek, Frank, and Smith, 1967; and Winters and Morgan, 1967). Let me tell you briefly about these research vehicles.

One (Figure 2) was a battery-powered car we called Electrovair II. This car used a 530-volt silver-zinc battery as its basic energy storage unit. The silver-zinc battery has about five times the energy storage capacity, and also about five times the power-handling capacity, as the same weight of typical lead-acid batteries with which we are all rather familiar. Since they contain a lot of silver, they are fearfully expensive—much too expensive ever to be practical for use in mass-produced automobiles. However, they represent the most advanced type of battery system available today for vehicle propulsion. Even so, they fall far short of the energy storage and power capabilities of an engine fueled with gasoline. The Electrovair II therefore weighed 3,400 pounds, which is 800 pounds (or about 30%) more than its counterpart, the standard 1966 Corvair. It also had an operating range of only 40 to 80 miles (depending on how it was driven), as compared to the 250- to 300-mile range of the standard 1966 Corvair with a full tank of gasoline. A weight and performance comparison is given in Table 3.

Figure 2. Electrovair II.

Table 3.

WEIGHT AND PERFORMANCE COMPARISON OF ELECTROVAIR II AND CORVAIR

	Electrovair II	Corvair
Weight, lb	3400	2,600
Acceleration (0 to 60 mph) sec	16	16
Top speed, mph	80	86
Range, miles	40-80	250-300
Power train weight, lb	1,230	610

The silver-zinc battery pack for the Electrovair II was composed of 286 cells, and it did not represent a serious development problem. It was quite otherwise, however, with the electric motor system (see Figure 3) that took the power from the batteries and converted it to torque at the wheels of the Electrovair II. In fact, this car was intended to be a test-bed to evaluate the electric motor drive system. This propulsion unit was newly developed for this application, as well as for others, and it used a set of high-power electronic switches called thyristors (or silicon controlled rectifiers—SCR's) to control its torque output. The more conventional direct-current electric motor utilizes a commutator instead of electronic switches, the commutator being in effect a set of mechanical switches for accomplishing much the same function. However, a mechanical commutator is limited to moderately low switching rates by mechanical and inductive sparking problems; on the contrary, however, the electronic switches are able to function at relatively high rates. Consequently, it is possible, using the high-power electronic switches in what we call the "modulating inverter assembly" (Figure 4) to design the motor to operate at greatly increased rotational speeds—about 13,000 rpm—the conventional direct-current electric motor operates at about 3,500 to 4,000 rpm in this horsepower range. These high speeds (at the same torque levels) imply, in turn, a correspondingly increased power-handling capacity for the same weight of motor. Table 4 gives a weight analysis for this motor system.

Table 4. WEIGHT ANALYSIS OF ELECTROVAIR II MOTOR AND RELATED CONTROL SYSTEM
(in pounds)

Motor	130
Gear box	25
Modulating inverter assembly	235
Control electronics	24
Cooling system	80
Cables, etc.	56
TOTAL	550

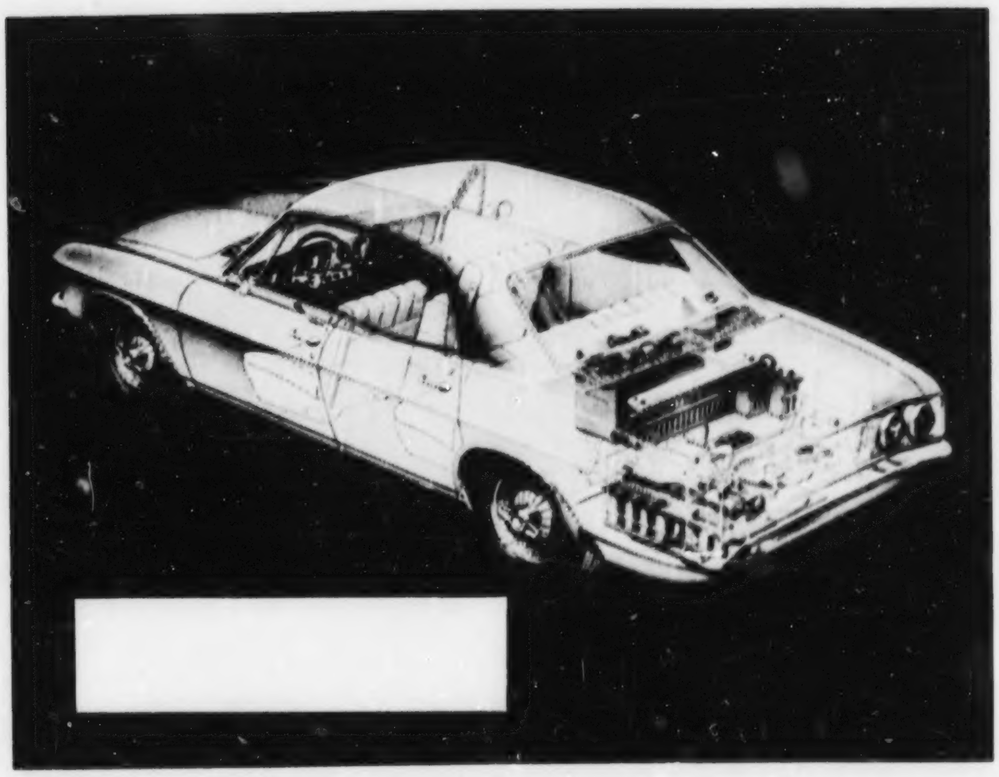

Figure 3. Electrovair II.

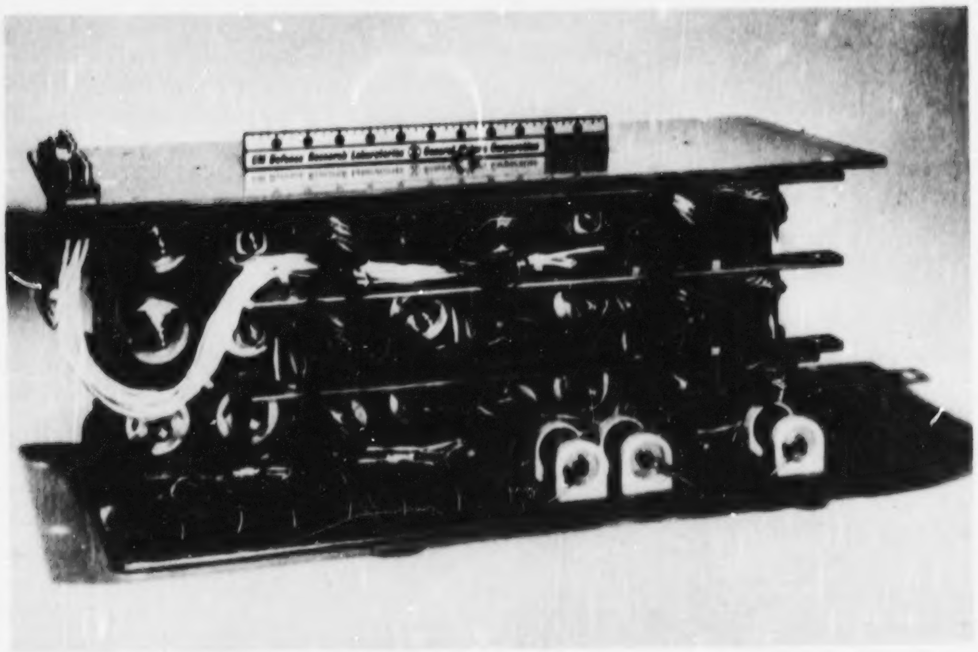

Figure 4. Modulating inverter.

Using such a high-speed motor system, we found it possible to deliver approximately 100 peak horsepower to the Electrovair II from a motor weighing only 130 pounds. The conventional type of direct-current motor in this same application would have required an estimated 500 to 800 pounds to yield the same number of horsepower. This extra motor weight would then have required further structural material and weight in the body of the vehicle, and all this extra weight would have produced correspondingly increased power and acceleration losses. By using the lightweight high-power motor controlled by electronic switches, it was possible to achieve acceleration performance in the Electrovair II comparable to the acceleration performance of the standard 1966 Corvair, despite the greater weight of the Electrovair II.

The electric car was simple to operate, but complicated in its control circuitry. The driver was required to manipulate only the steering wheel, brake, an on-off switch, a forward-neutral-reverse lever, and an accelerator pedal that provided smooth, "step-free" acceleration and speed control over the whole operating range. Figure 5 shows (schematically) the car's control circuitry. The low-power logic circuits were required to shut off the main battery power if anything went seriously wrong, to prevent over-speeding or over-accelerating, to prevent sudden reversals of output torque under any conceivable malfunction condition, and so forth. It is very important, of course, that adequate safety features be built into such a car, because the hazards are otherwise significant; at the same time and for the same reason, it is very important that the operating procedures required of the driver be extremely simple, smooth, and similar in character and effect to what he is already accustomed to.

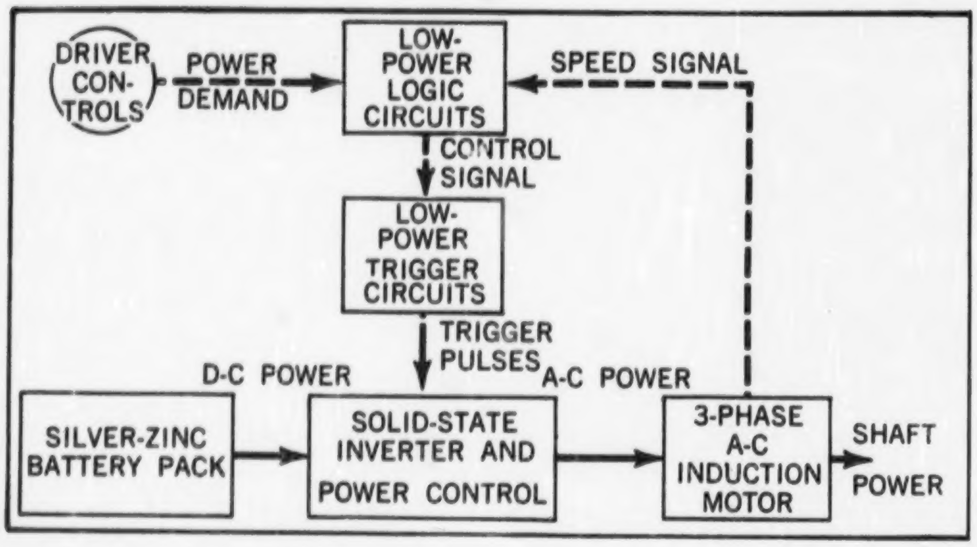
DRIVER CON-TROLS
POWER DEMAND
LOW-POWER LOGIC CIRCUITS
SPEED SIGNAL
CONTROL SIGNAL
LOW-POWER TRIGGER CIRCUITS
TRIGGER PULSES
D-C POWER
A-C POWER
SILVER-ZINC BATTERY PACK
SOLID-STATE INVERTER AND POWER CONTROL
3-PHASE A-C INDUCTION MOTOR
SHAFT POWER

Figure 5. Control circuitry for Electrovair II.

Our second experimental vehicle powered by electricity (Figure 6) was called the Electrovan; it was produced mainly for study, on an experimental basis, of the problems of powering a passenger vehicle with an electric fuel battery. The fuel cell modules were developed by Union Carbide, and we developed the means of putting them together into a successful fuel battery.

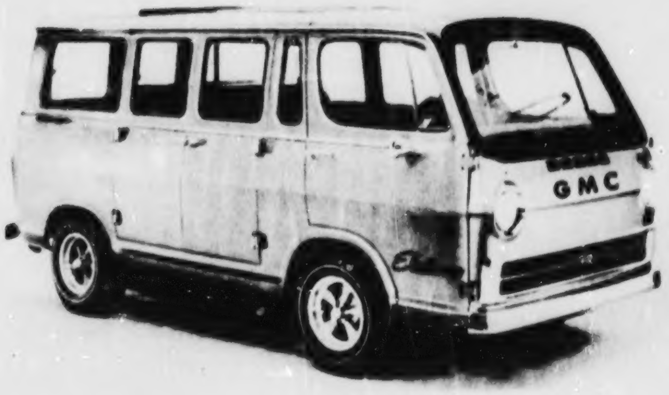

Figure 6. Electrovan.

Figure 7 shows a phantom view of the Electrovan with its electric drive train displayed rather completely. In this van you will note that we used a battery composed of 32 fuel cell modules connected in series to produce an open circuit voltage of 520 volts. This battery had a power capacity of 32 kilowatts continuous and 160 kilowatts for short time periods. Almost the same drive motor system was used in the van as was used in the Electrovair, but in the van it was able to produce 125 horsepower, instead of the 90 or 100 that it developed for the Electrovair, because the fuel battery voltage in the van did not sag as much under load as did the voltage of the silver-zinc battery in Electrovair.

The van's fuel battery uses pure hydrogen as the fuel and pure oxygen as the oxidizer; these can be stored either in high-pressure containers or in liquid form at very low temperatures. A little study—summarized in Table 5—shows that cryogenic storage is best.

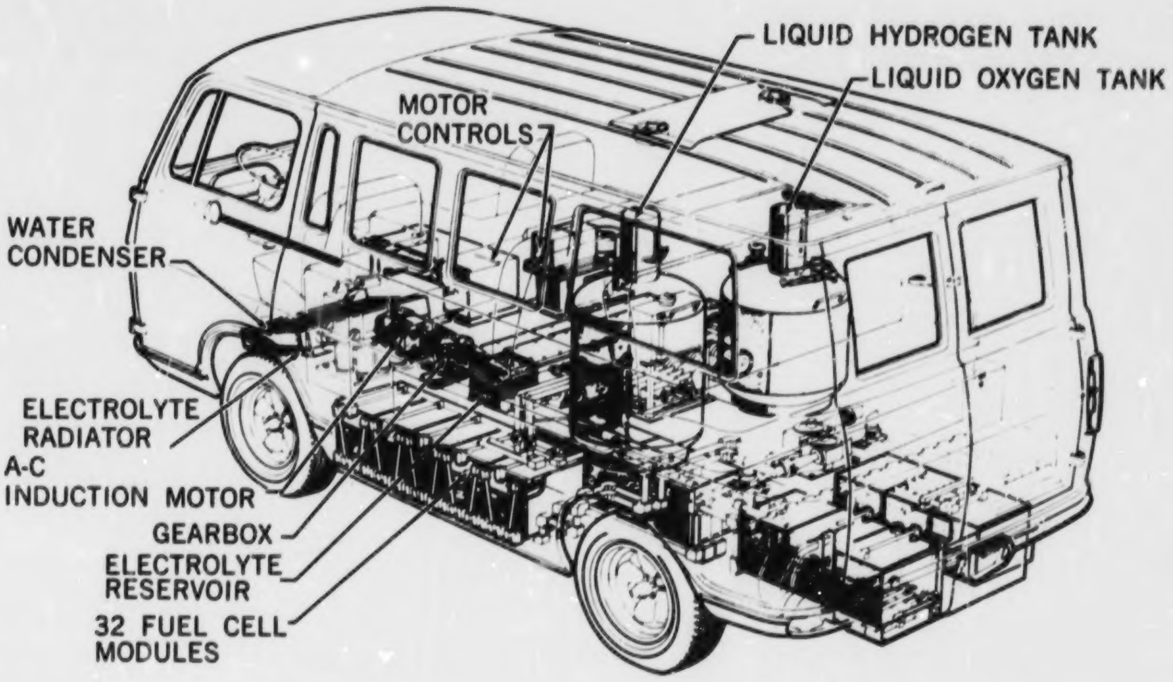
LIQUID HYDROGEN TANK
LIQUID OXYGEN TANK
MOTOR CONTROLS
WATER CONDENSER
ELECTROLYTE RADIATOR
A-C INDUCTION MOTOR
GEARBOX
ELECTROLYTE RESERVOIR
32 FUEL CELL MODULES

Figure 7. Phantom view of Electrovan.

Table 5. COMPARISON OF WEIGHT, VOLUME, AND RANGE CHARACTERISTICS OF CRYOGENIC AND COMPRESSED GAS FUEL SYSTEMS

Item	Cryogenic	Compressed gas at 5000 psi	Ratio
Total volume, ft^3	13	6	2.2
Total weight, (incl. vaporizers), lb	389	358	1.1
Total weight of product, lb of H_2 and O_2	108	47	2.3
Total specific volume ft^3 per lb H_2 and O_2	0.12	0.13	0.9
Total specific weight, lb/lb H_2 and O_2	3.6	7.6	0.5
Range, miles	100 to 140	45 to 65	2.3

I want to point out most emphatically, however, that stored hydrogen and oxygen gases, whether at high pressure or at low temperature, would not be satisfactory or practical as an energy source for passenger vehicle transportation.

Figure 8 shows the four loops of plumbing used in our Electrovan. These loops contained hydrogen, oxygen, liquid potassium hydroxide in aqueous solution, and cooling air. Keeping leaks out of all this plumbing was of course a major headache during the debugging of the van.

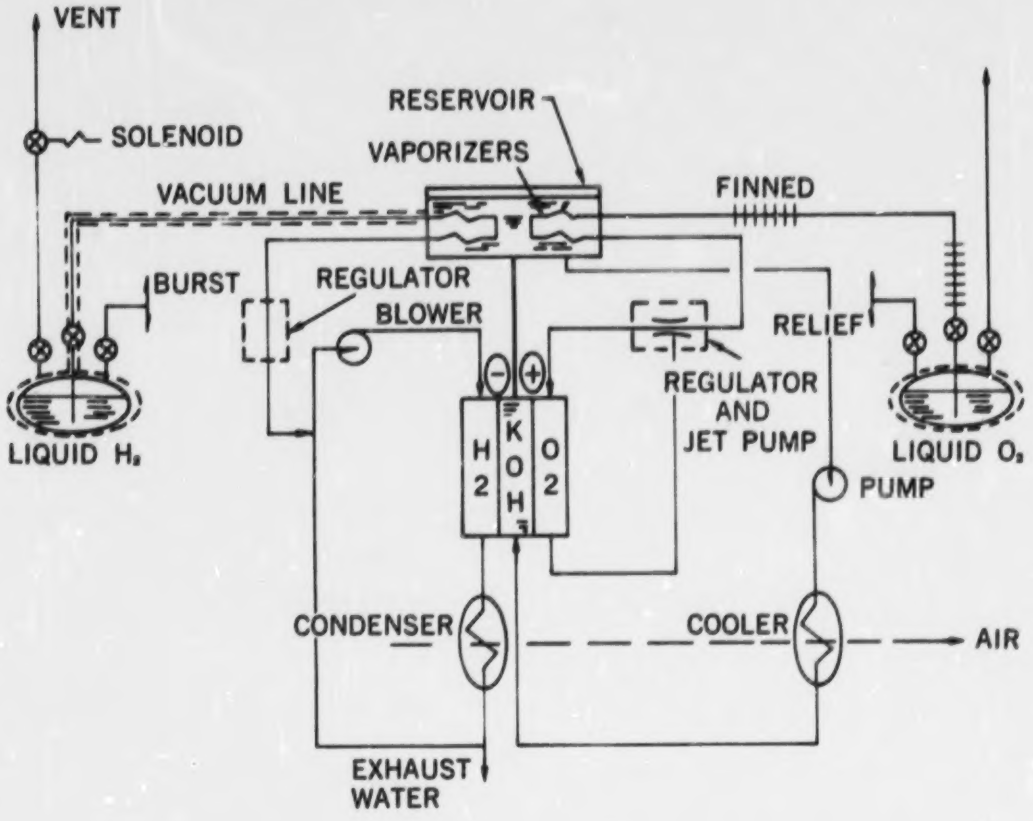
VENT
SOLENOID
RESERVOIR
VAPORIZERS
VACUUM LINE
FINNED
BURST
REGULATOR
BLOWER
RELIEF
REGULATOR
AND
JET PUMP
LIQUID H₂
LIQUID O₂
PUMP
⊖
⊕
H 2
K O H
O 2
CONDENSER
COOLER
AIR
EXHAUST
WATER

Figure 8. Schematic of Electrovan fluid system.

Figure 9 shows the electrical diagram of the fuel battery system of the van. Since the potassium hydroxide electrolyte had to be circulated to cool the modules, there was an electrical shunt across the fuel battery through this electrolyte circulation loop. Our plumbing design was aimed at minimizing this electrical leakage, but even so it amounted to 2.4 kilowatts.

Table 6 shows the weight analysis and performance levels achieved with the Electrovan compared with those of a standard production van.

At this point I should mention that we are interested not only in the purely technical problems involved, but also in all aspects of potential markets for our electrochemical power systems and their associated electric drives. Some possible applications under study are listed below:

- Small cars
- Full-size cars
- Taxis and busses
- Light, medium, and heavy trucks
- Locomotives
- Off-road trucks and scrapers
- Industrial variable-speed drives
- Load levelers for utilities

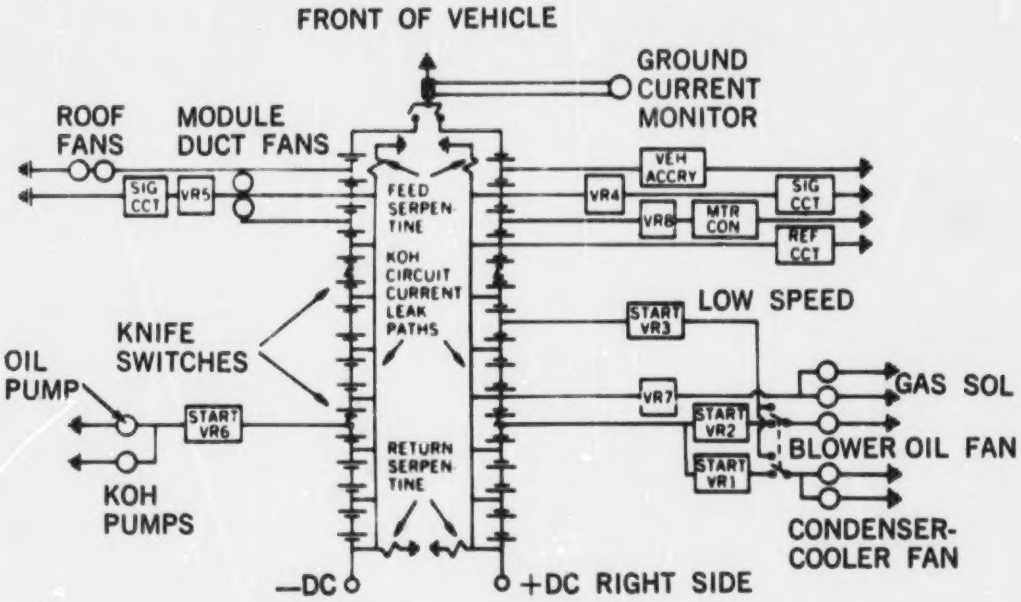
FRONT OF VEHICLE
GROUND CURRENT MONITOR
ROOF FANS
MODULE DUCT FANS
SIG CCT
VR5
FEED SERPENTINE
KOH CIRCUIT CURRENT LEAK PATHS
RETURN SERPENTINE
VEH ACCRY
VR4
SIG CCT
VR8
MTR CON
REF CCT
START VR3
LOW SPEED
KNIFE SWITCHES
OIL PUMP
START VR6
KOH PUMPS
VR7
START VR2
START VR1
GAS SOL
BLOWER OIL FAN
CONDENSER-COOLER FAN
—DC
+DC RIGHT SIDE

Figure 9. Schematic of Electrovan fuel cell electrical system.

Table 6. COMPARISON OF PERFORMANCE AND WEIGHTS OF ELECTROVAN AND GMC PRODUCTION VAN

	Electrovan	GMC van
Total vehicle weight, lb	7,100	3,250
Fuel cell powerplant weight, lb	3,380	
Electric drive weight, lb	550	
Powertrain total weight, lb	3,930	870
Acceleration (0 to 60 mph), sec	30	23
Top speed, mph	70	71
Range, miles	100 to 150	200 to 250

Many of these markets are highly dynamic and are influenced not only by economic, but also by political and psychological, pressures.

In summary:

1. Potential advantages of electric vehicles include quiet operation, efficiency not limited by heat engine cycle, reduction of emissions, and use of low-cost electricity generated by nuclear reactors when fossil fuels become more scarce.
2. Research on electric vehicles offers potential for commercial payoff in many other fields.
3. Any power system, considered in the whole, presents possible pollution problems.
4. It is still too early to state definitely that any kind of electric automobile will soon be able to win an economically significant and viable place for itself in the total transportation picture.

Returning to comment briefly on the first of these points, the single most important reason for the current strong resurgence of interest in electric motor cars is the growing problem of air pollution; however, we are also interested in electric vehicles because the development of efficient and constantly improved systems of energy conversion is vital to the automotive transportation industry. For this reason, we will continue to pursue aggressively any method of energy conversion that offers potential for improving our vehicles.

I should like to mention at this point that if one is willing to accept the relatively low performance levels currently promised by the all-electric automobile, then we should also take a careful look at how much emissions can be reduced from a car powered by a small internal combustion engine that features the same performance level as the all-electric. Emission level comparisons can only be validly made on the basis of comparable performance levels.

Concerning the second point, greatly improved batteries and also improved electric motors are going to be needed if millions of electric cars on the highways are ever to become a practical reality. As far as energy storage and power-handling capacity is concerned, passenger cars with internal combustion engines perform very well indeed. Consequently, much improvement in batteries and electric motors is needed if they are to be able to perform approximately as well as the internal combustion engine. Even if we are not able, in the near future, to achieve the high levels of performance required for a truly practical electric passenger vehicle, improved batteries and motors will undoubtedly produce commercial payoffs in other applications. We are interested in improving the electric power train of diesel locomotives, for example. We are interested in improving our starter batteries. So we believe we have justification for pushing ahead with our research and development in all these fields.

Turning to the third point, the fact is often overlooked that any power system creates pollution problems. Suppose, for example, one has a completely sealed battery that draws and stores energy from an electric wall plug and delivers it on demand to the wheels of the car. This would appear to be a power system wholly free of pollution problems. However, power drawn from the wall plug has to be generated somehow, and presently it is generated by a central power-generating plant that uses oil or coal as fuel. This plant has an exhaust stack, of course, and at all times emits oxides of sulfur, nitrogen, and carbon, because these are combustion products when coal or fuel oil is burned in air. Oxides of sulfur and nitrogen are, of course, some of the major offenders in air pollution. Carbon monoxide is another undesirable pollutant if present. However, it usually is not found in significant amounts in power plant stack gases.

Of course, many technologists believe that most of our energy in the future will be generated by large nuclear reactors. However, these reactors have pollution problems too, since radioactive waste products are generated and have to be disposed of appropriately.

Consequently, we see that any power system, considered in the whole, generates some sort of pollution problems.

With respect to the fourth point, it is believed that electric vehicle propulsion is *technically* feasible. However, our research has not indicated *when* it would be *economically* feasible or *acceptable* to customers in terms of safety, utility, and convenience.

In some applications, such as diesel-powered locomotives, electric drives have thus far demonstrated their capacity to do the job better than mechanical power trains. However, the personal passenger vehicle imposes its own very stringent and special requirements on its power train. Many American passenger cars are required to have a heated cabin when it is cold outside, an air-conditioned cabin when it is not cold outside, several powerful headlights, electric window lifts, a radio, a record player, and other convenience items. All these take power—in some cases as much power as is required to propel the car along the road at moderate speed. The modern American passenger car requires peak power levels five to seven times larger than it uses at urban speeds Moreover, it is frequently driven hundreds of miles with only a few brief stops for "re-energizing." Hence, the major obstacle to the early mass use of an all-electric car is the present day lack of an adequately high-power plus high-energy-capacity storage or fuel battery at reasonable cost. Some batteries have good power but poor energy storage capacity, some have the reverse, but none is adequate in both areas at once.

We know that any vehicular power plant must be developed first for technical feasibility, next for producibility and cost, then for durability under engineering test, and finally for safety, reliability, and convenience in the hands of the public.

At this time not all the answers to attaining these goals with electric power are known. Consequently, we believe that our extensive research and development work must be continued if we are to continue to make necessary progress in energy conversion.

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EUROPEAN DEVELOPMENTS OF POWER SOURCES FOR ELECTRIC VEHICLES

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INTRODUCTION

The immediate availability of conventional storage batteries has stimulated in Europe the building of a number of small electric vehicles for testing. At the same time many companies have initiated programs on the research and development of novel devices such as fuel cells. The progress of this work on passenger-carrying vehicles and power systems is reported here.

The use of electric power to drive automobiles is by no means new. In 1899 M. Jenatzy, a Belgian racing driver, momentarily won the world speed record at 65.8 mph with his electric car La Jamais Contente when he defeated a fellow racing driver, the Comte de Chasseloup-Laubat, also driving an electric car (Electricity Council, 1966). Unfortunately, shortly afterwards, Jenatzy forsook his first love and turned to the gasoline internal-combustion-engine vehicles, which at the turn of the century, because of their greater range and speed, were rapidly ousting the electrics from popular favor in many cities in the United States as well as in Europe. With the proliferation of the internal-combustion engine we now face the menace of chronic traffic congestion in the cities, as well as the acute discomfort and hazards to health caused by noise and noxious fumes. On the latter point, it has been estimated that about 5 million tons of carbon monoxide belch forth from the exhaust pipes of the world's internal-combustion-engine vehicles each year. This is equivalent to a daily output of this lethal gas of about 400 million cubic feet; in addition the vehicles emit quantities of partly oxidized hydrocarbons, some of which are believed to be carcinogenic.

It is worth noting that the internal-combustion engine is consuming its fuel and pouring out noxious fumes even when the vehicle is stationary and idling in traffic. This does not apply to an electric vehicle.

The wheel has now turned full circle. Interest in electric automobiles has been re-kindled in many of the highly developed countries of the world. What factors led to the demise of these vehicles, and how can they be resuscitated?

THE POWER UNIT

The obvious deficiency lay in the power unit. Lead-acid and nickel-iron alkaline storage batteries have to date provided the only source of power sufficiently reliable and durable to meet industrial and commercial requirements. But these systems have relatively low power densities, in the range of 10 to 15 watt-hours per pound for a running time of 2 to 5 hours, so that a large weight of battery has to be carried to provide horsepower equivalent to that of even a small automobile. For 10 horsepower, for example, this amounts to between 1,000 and 1,500 pounds.

A few years ago the silver oxide-zinc couple made a meteoric appearance on the battery scene, offering a four- to five-fold increase in the energy density of the conventional storage batteries. Unfortunately, it proved to have poor reversibility and a low cycle life in multicell systems and this, together with the high material cost, has restricted its commercial use.

More recently still, fuel cells have received much publicity. Theoretically and in fact on the laboratory scale, these systems offer a considerable reduction in weight, although not in overall volume, and they offer the added advantage that the fuel can be replenished in about the same time as would be taken to refill the gasoline tank of a conventional automobile. Fuel cells are therefore attractive for this purpose, but they are complex systems and rather expensive to make, and at present, the most effective fuels are expensive or difficult to handle. Hybrid systems sometimes called semi-fuel cells, having a metal anode, such as zinc — as in storage batteries — and a fuel-cell-type cathode consuming oxygen or air such systems are under development both in primary and reversible forms and show some promise. Reversible semi-fuel cells, like storage batteries, however, have the disadvantage that several hours are required for recharging.

Within the past few months disclosures have been made of new electrochemical couples, in particular sodium-sulphur and lithium-chlorine. These show, on paper at least, the highest energy densities attainable so far, but for various reasons, they have to be worked in the temperature ranges 300° to 500°C and 500° to 650°C, respectively. A preheating source is therefore necessary, and these systems would probably have to carry a considerable amount of insulation for intermittent use. Also, the active materials would present dangerous hazards in the event of an accident.

ENERGY DENSITIES OF DIFFERENT SYSTEMS

Figure 1 shows the energy densities in watt-hours per pound for different durations of discharge for various systems mentioned (Barak, 1965). The values given for the Bacon hydrox cell, consuming hydrogen and oxygen and working at temperatures around 200°C and pressures of 600 psig, include the estimated weight of all the ancillary equipment and are still the most favorable for fuel cell systems.

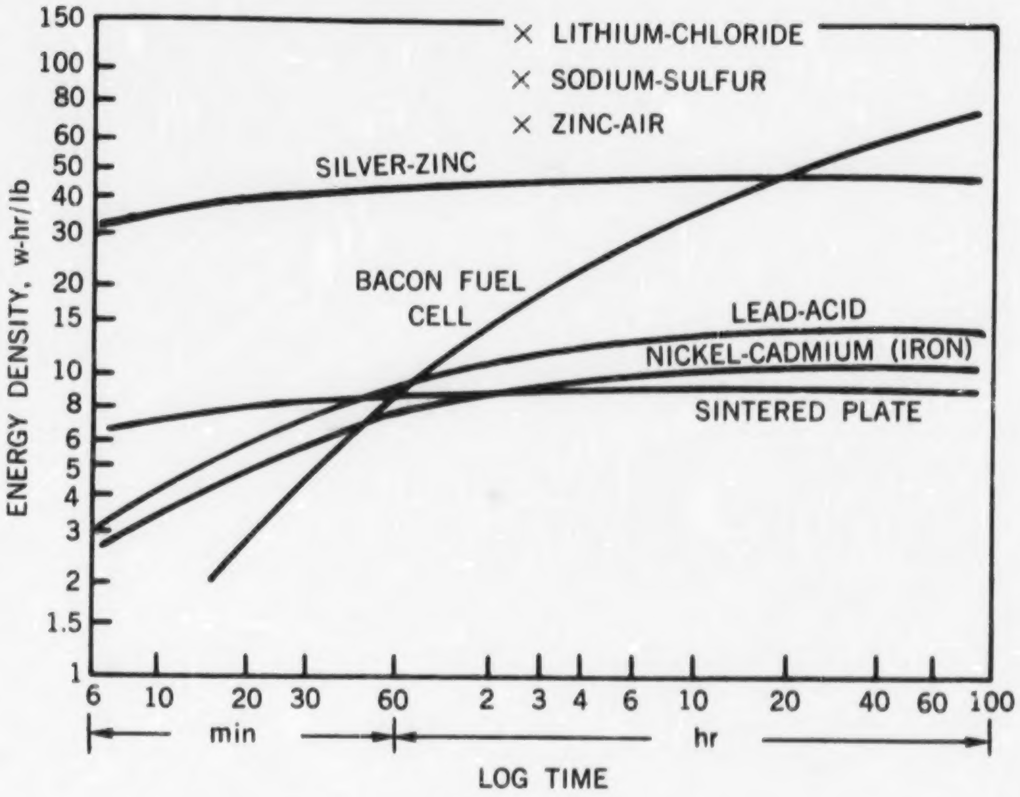


Figure 1. Energy densities at different rates of discharge for various battery systems.

These curves indicate that for continuous durations of discharge of less than about 1 hour, storage batteries have a higher density than fuel cells. This becomes more and more pronounced as the current approaches starter battery currents. It is unlikely, therefore, that any of these other systems will displace conventional storage batteries for this service in internal-combustion-engine vehicles. On the other hand, for periods of discharge of about 2 hours and longer, common to traction service, fuel cells show a continuing superiority over storage batteries. The position of the semi-fuel cells and the new high-temperature storage batteries should be noted.

DEVELOPMENTS IN ELECTRIC TRACTION

Work on electric passenger vehicles is being actively carried out in Great Britain. The climate is particularly favorable because electric vehicles for industrial and commercial uses have been popular for a long time. Hender (1965) has shown (Figure 2) how the number of battery-electric vehicles registered for road use increased between 1953 and 1964. These now number over 40,000, and with the 70,000 battery-operated electric industrial trucks, make a total population of about 110,000.

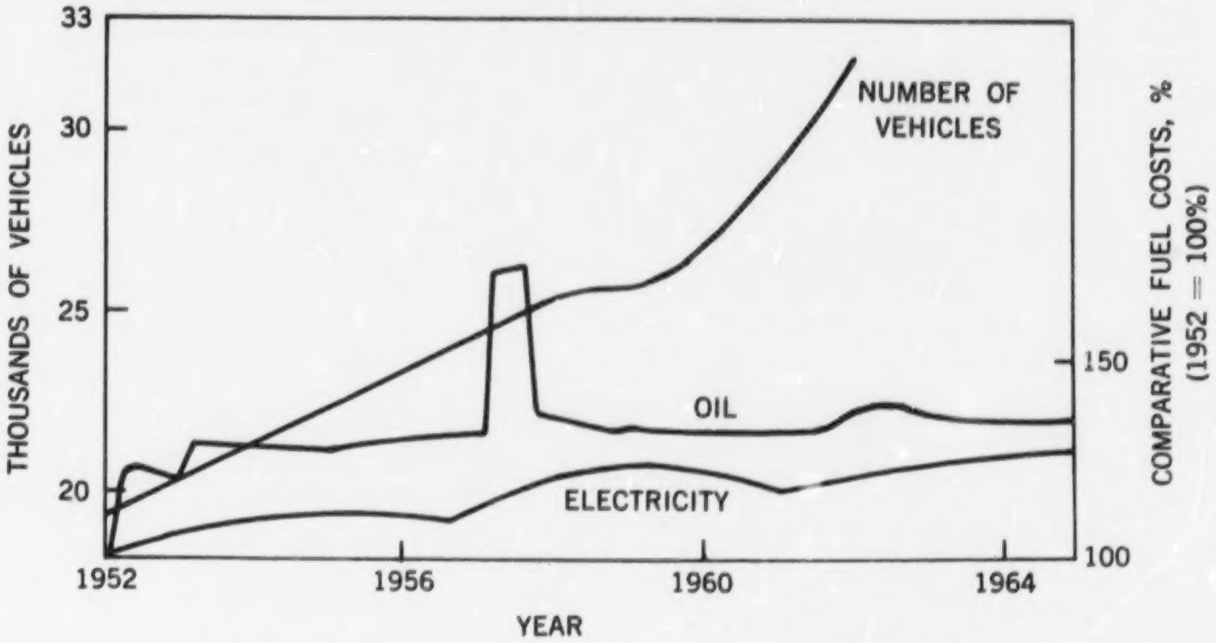


Figure 2. Increase in the number of battery-electric vehicles registered for road use (excluding p.c.v.s.) with comparative fuel costs of oil and electricity.

Experience over many years has proved that, in Great Britain at least, the fuel and maintenance costs are less for an electric than for an internal-combustion-engine truck; the life expectancy is appreciably greater, and there are other benefits, such as freedom from noise and fume. The favorable cost of electricity compared with fuel oil is indicated by curves a and b in Figure 2. Some comprehensive figures for economies in depreciation, maintenance, and running costs achieved by the use of electric fork-lift trucks are given in *The Electric Industrial Truck*, published by the Australian Lead Development Association, 95 Collins Street, Melbourne. The annual figures for depreciation and maintenance of an electric vehicle are estimated to be only 51 percent of those for a diesel truck and the economy in fuel, 67 percent. Within recent years also, considerable improvements have been made in the energy density of storage batteries of both the tubular type and the flat plate-glass retainer types. For example, at the 5-hour rate, the gains in watt-hours per pound and watt-hours per cubic inch have been about 35 percent, and at the 30-minute rate, about 40 percent (Barak, 1965).

The advent of new materials, e.g., lighter and stronger plastics suitable for battery cases, and of improved designs to reduce the proportion of inert metal in the battery will undoubtedly allow still further gains. Unfortunately, though significant, these gains will be marginal and it is unlikely that spectacular improvements will be achieved again.

Several electric passenger vehicles with storage batteries as the power unit have been produced during the past few years. Four of these were recently demonstrated by the Electricity Council and described by K. W. C. Jeremy(1966). Three were conversions of internal-combustion-engine cars, but the fourth, the Scamp, made by Scottish Aviation Ltd., was specially designed for the purpose. The objective was a "town-about" car, small enough to avoid traffic congestion, easy to maneuver and park, quiet and fumeless, and therefore a noncontributor to the smog problem, with a fairly lively performance, and a range of about 20 to 30 miles.

The characteristics of one of the converted Mini-travellers made by the British Motor Corporation and the Scamp are given in Table 1.

Table 1. CHARACTERISTICS OF THE MINI-TRAVELLER AND THE SCAMP

	Mini-traveller	Scamp
Curb weight, lb	2,499	1,000
Motor	V67 type made by AEI, Ltd., with chain drive to original differential.	Twin, made by CAV, Ltd., driving onto each rear wheel
Rating	96 v, 110 amp equiv to 12 hp	24 v, 150 amp (each) equiv to 2.7 hp
Weight, lb	178	
Battery	96 v, 66 amp-hr (1 hr)	45 v, 105 amp-hr (5 hr)
Power, kw	6.3	1
Energy, kw-h	6.3 (1 hr)	5 (5 hr)
Weight, lb	830	400
Controls	Thermistor pulse unit with regenerative braking	
Weight, lb	110	
Maximum speed, mph	41	35
Range, miles	30	15-20

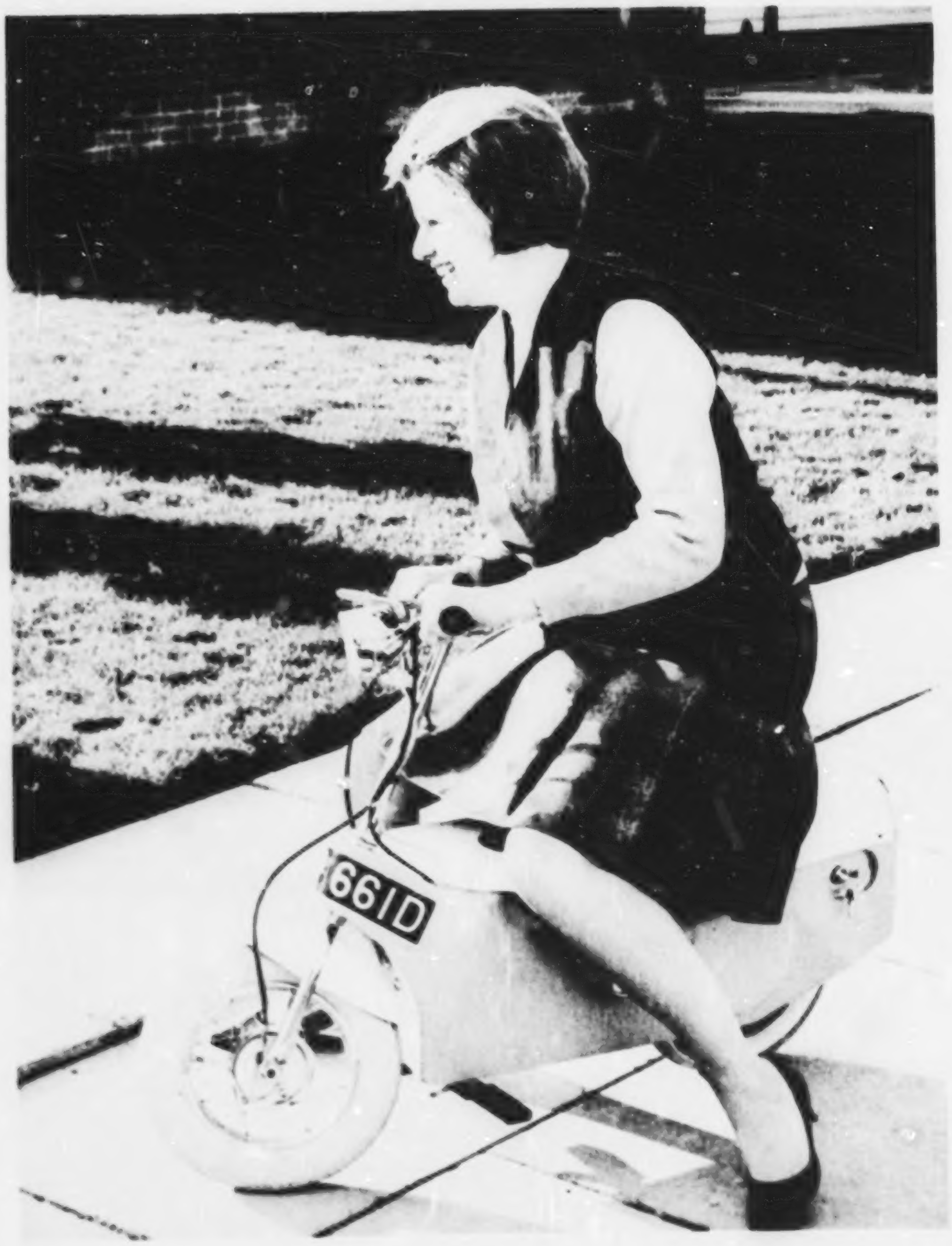
The range of these cars is generally regarded as being too low. Range should be nearer 100 miles on one charge, and this calls for a system with higher energy density.

Table 2 lists some of the salient features of the storage battery on the Mini-traveller and also the minimum specification for an energy source to meet this requirement.

I will mention various other custom-built cars under construction and present photos of some of these.

The Carter Coaster is made by Carter Engineering Co., of Tamworth, Staffordshire. This vehicle is expected to have a top speed of about 30 mph and a range of 40 to 50 miles.

The Winn car is made by the Telearchics Ltd. of Lechlade, Gloucestershire, who are also developing battery-propelled motorcycles.



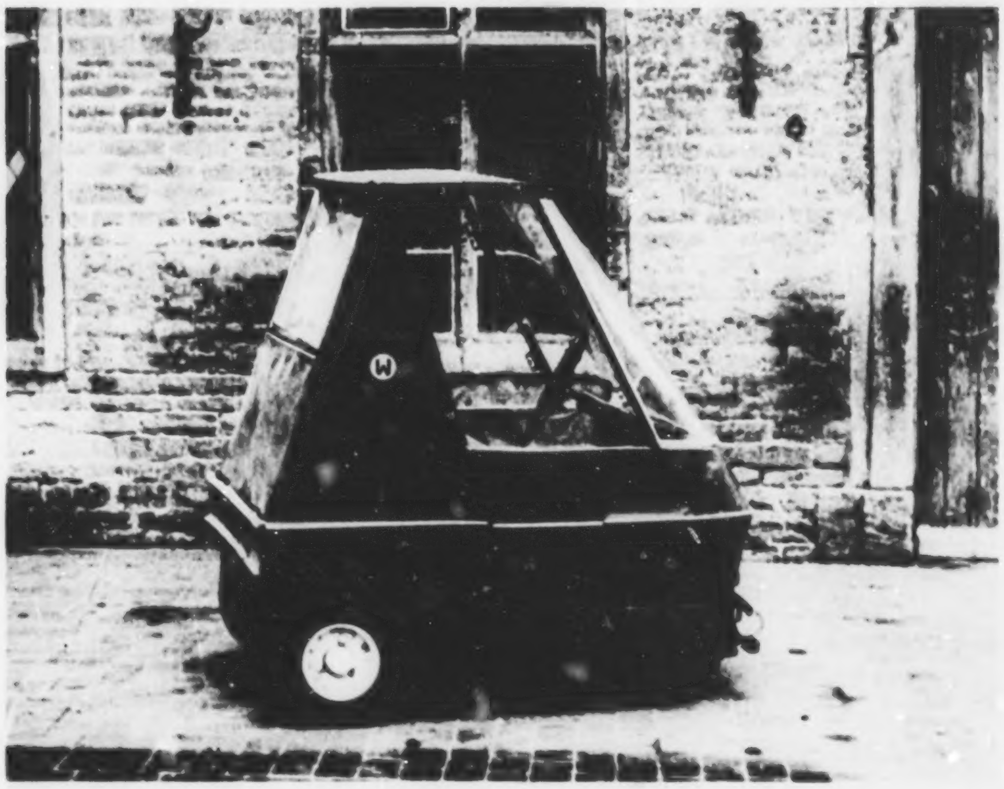


Table 2. STORAGE BATTERY CHARACTERISTICS AND SPECIFICATIONS

	Storage battery	Minimum specifications
Power	96 v, 66 amp-hr (1 hr)	25 kw-h (2 hr)
	6.3 kw-h or kw	
Weight, lb	830	< 1,000
Watt-hr/lb	7.6	25 to 30
Volume, ft^3	5	6
Watt-hr/ft^3	1,300	2,000
Range at 30 mph, miles	30	50 to 100
Life, cycles	1,500 to 2,000	> 1,000
years	5 to 6	4
Costs, capital	£150 ($420)	< £250 ($700)
£/kw	£23 ($64)	£20 ($56)
recharging	0.8d/kw-h (0.93¢)	
or refueling	0.33d/mile (0.38¢)	

Note: The cost of petrol (gasoline) in Great Britain is about 5s 3d (73 cents) per gallon; for a medium-sized car consuming about 1 gallon each 30 miles this is equivalent to a cost of about 2 d (2.3 cents) per mile.

Tube Investments Ltd., has built a small-two seater city car with an all-in curb weight of about 1,000 pounds. It is powered by lead-acid storage batteries of 48 volts and 350 pounds weight. This vehicle is fitted with a semiconductor-controlled rectifier (SCR) pulse-controller system of novel design, developed by Lansing-Bagnall Ltd. Tests have been made over several hundred miles and the range in open country at a speed of about 25 mph is 50 to 60 miles. On tests in commuter traffic this car has traveled 27 miles with 117 stops on one charge.

Ford Company of Great Britain is building two models ultimately to be fitted with the sodium-sulfur batteries under development at the Research and Development center in Detroit. It is understood that the initial trials will be made with conventional storage batteries.

An interesting development in France is a battery-powered bus made by Sovel for operation in the airport of Marseilles. In Italy the Fiat Company is understood to be experimenting with electric cars. The Urbanina, made by Bargagli Cristiani of Santa Groce, a small car for town use, of very novel design, was recently demonstrated at the Italian Motor Show.

All of these vehicles are powered by the well-proved lead-acid storage batteries. Recognizing the limitation imposed by the weight of these batteries, engineers are examining all aspects of the vehicle to obtain the best performance possible, e.g., the use of SCR pulse-control systems to ensure the maximum efficiency of use of the battery, design of chassis and body to keep the weight to a minimum and provision of regenerative braking, which is estimated to increase economy of power by 15 to 30 percent.

FUEL CELLS AND METAL-AIR CELLS

Three industrial companies in Great Britain are actively engaged in developing fuel cells, some of which could be used to power electric vehicles. Shell Research Ltd., who has demonstrated units of about 1-kilowatt capacity with an alkaline electrolyte consuming hydrazine and hydrogen and a 5-kilowatt hydrogen-oxygen battery linked to a methanol reforming unit, has lately turned attention to cells with acid electrolyte, breathing air. Figure 3 shows a 300-watt battery of this type with a sulfuric acid electrolyte (private communication with K. R. Williams, Shell Research Ltd.). Two marked advances have been made recently. The first concerns the use of porous plastic substrates with higher temperature stability than materials used earlier; the second concerns the hydrogen and oxygen electrodes, which are now capable of working at current densities as high as 500 milliamperes per square centimeter in sulfuric acid at a cell voltage of 0.6 volt.

Energy Conversion Ltd., who is associated with Pratt and Whitney Co. and is working on a variety of systems, has recently developed a methanol-air battery with internal reforming and hydrogen diffusion membranes of palladium-silver alloy. A 4-"bi-cell" is shown in Figure 4 (private communication with J. C. Hart, Energy Conversion Ltd.). This works at 200° to 250°C and has an output of about 170 watts at 2.7 volts overall. By virtue of their agreement with Leesona Moos, Energy Conversion Ltd. is also engaged in work on the zinc-air system.

Electric Power Storage Ltd., a member of the Chloride Group of Companies, has been working primarily with hydrogen-oxygen or air and hydrazine-oxygen or air cells (Barak, 1963). Many 60-watt cell modules of each type have been built and have given satisfactory lives up to 10,000 hours on test (Gillibrand and Gray, 1966). Typical cells are shown in Figures 5 and 6. Batteries of 1 to 2 kilowatts have also been built. Figure 7 shows a 2-kilowatt hydrogen-oxygen battery of 63 cells, having an overall voltage on load of about 36 volts mounted on a small industrial truck.

Joseph Lucas and Co. has recently announced association with General Dynamics in the development of semi-fuel cells of the zinc-air type; experimental work on these systems is also being done by Energy Conversion Ltd., and by Electric Power Storage Ltd.

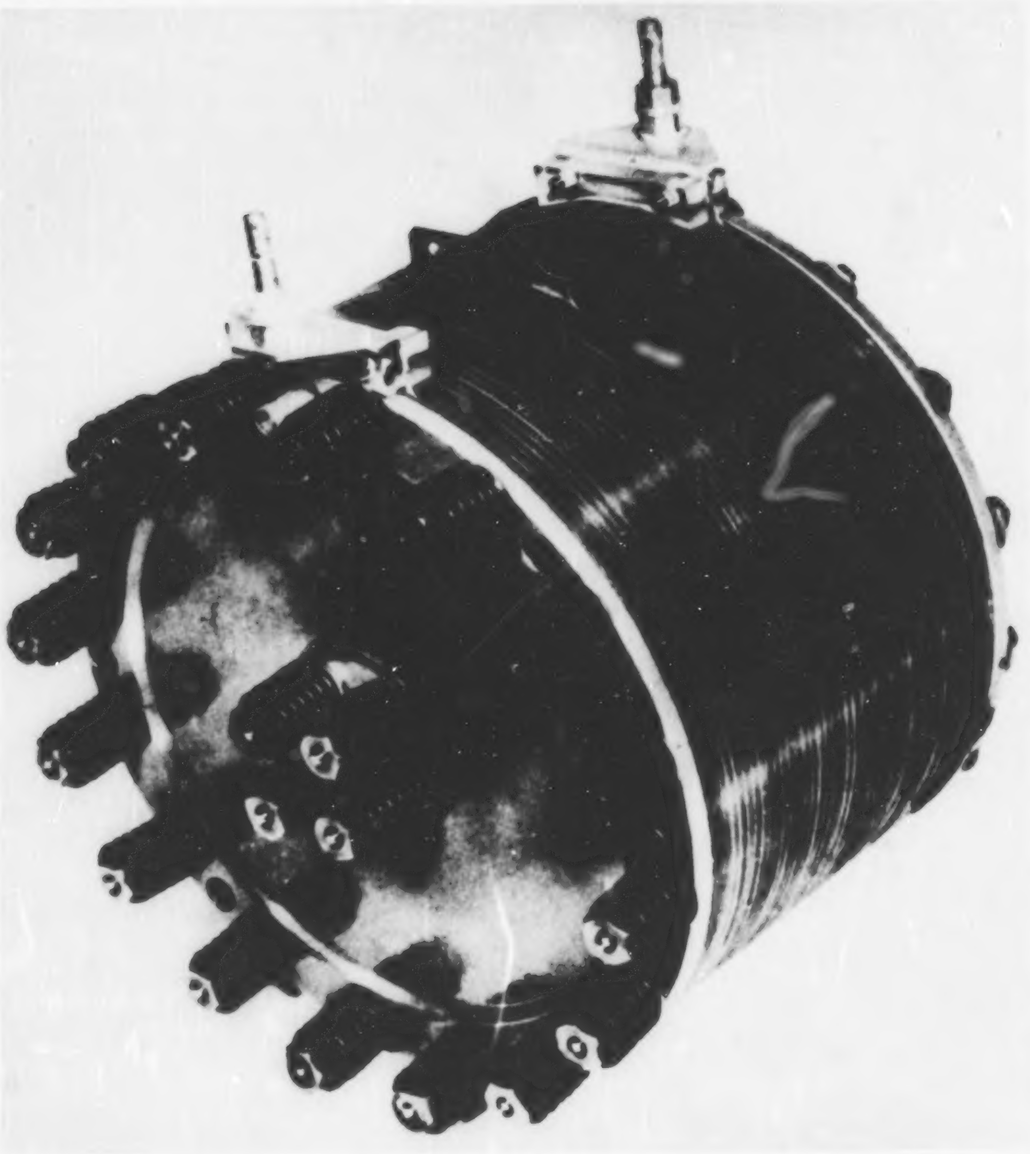


Figure 3. 300-watt methanol-air battery with sulfuric acid electrolyte (Shell Research, Ltd.).

OTHER DEVELOPMENTS IN EUROPE

In Germany, the Varta Company has been engaged in fuel cell development for some years and recently demonstrated a fork-lift truck powered by a hydrogen-oxygen fuel battery of about 2 kilowatts with an overload factor of about 3. This battery has electrodes of the sintered nickel, DSK type developed by Justi (1962), giving energy densities of about 10 watts per pound and about 1 kilowatt per cubic foot (Justi and Winsel, 1962).

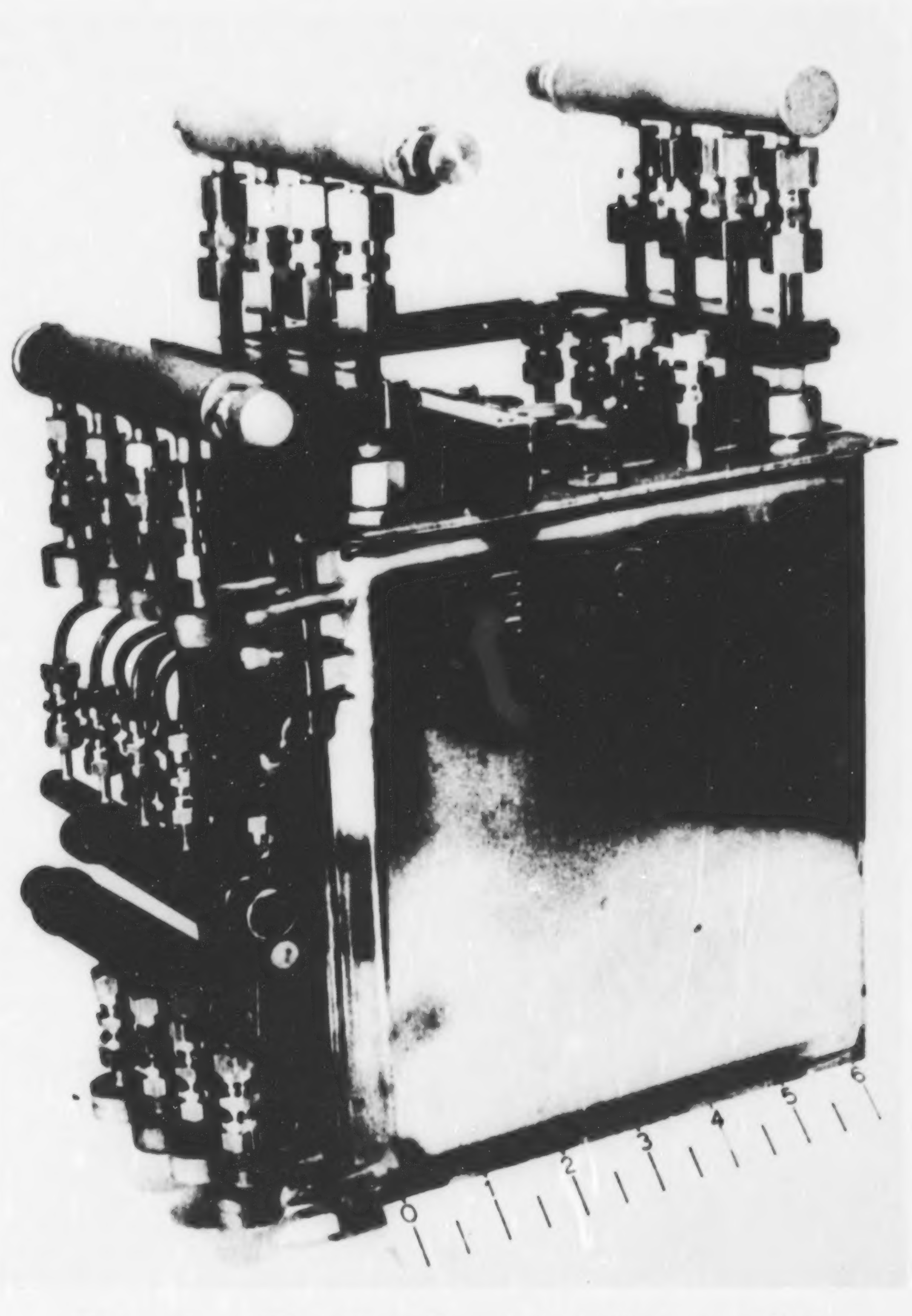


Figure 4. 120-watt methanol-air battery operating at 200°C (Energy Conversion, Ltd.).

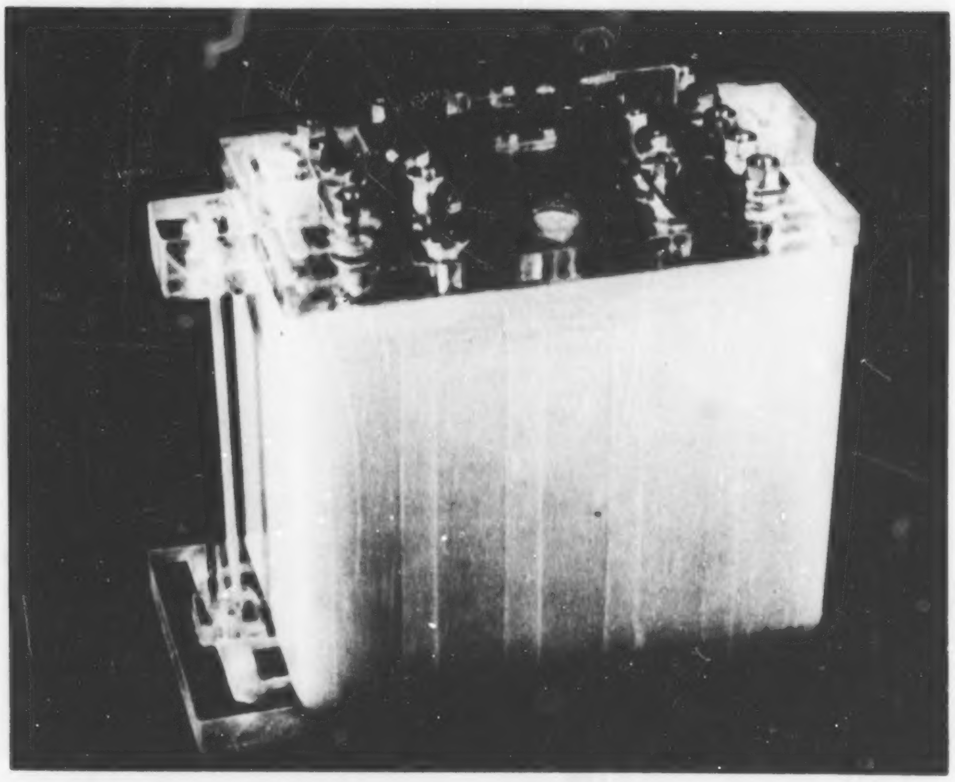


Figure 5. 60-watt, low-temperature, H_2-O_2 cell (Electric Power Storage, Ltd.).

Siemens-Schuckertwerke has also experimented with hydrogen-oxygen fuel batteries as a means of propulsion. Using electrodes of the Justi type, Siemens has built a 24-volt assembly with an output of about 400 watts to power a small boat. (Sturm, Nischik and Weidlick, 1966). Siemens has stated however, that "predictions of fuel cells entering into the fields of automobiles and large-scale power generation are purely speculative and must be considered unrealistic in the light of present knowldge" (Sturm, 1966).

In France, the Office National Industrial de l'Azote (O.N.I.A.) has experimented with cells of the Bacon type working at about 200°C and at both high and atmospheric pressures (Laroche, 1965). Units up to 2 kilowatts have been constructed, and a battery of 20 kilowatts is under development. To avoid the problem of carrying heavy bottles of gas, O.N.I.A. is developing batteries with built-in units such as ammonia-crackers to produce on-site hydrogen.

Compagnie Générale d'Electricité (C.G.E.) is engaged in work on low-temperature hydrogen-oxygen cells and has produced units with outputs up to 1 kilowatt (24 volts) (C.G.E., 1966).

In Sweden, Allmana Svenska Elektricka Aktiebolaget (A.S.E.A.) is carrying out a considerable program of work in the development of low-temperature hydrogen-oxygen fuel batteries (Lindstrom, 1966). Using sintered nickel electrodes of their "quadrus" type with nickel boride catalyst, A.S.E.A. has made a number of 5-kilowatt units, some of which have been tested on fork-lift trucks and also on other large industrial trucks. A.S.E.A. is also building a 200-kilowatt unit that consumes hydrogen from an ammonia cracker to power a coastal submarine.

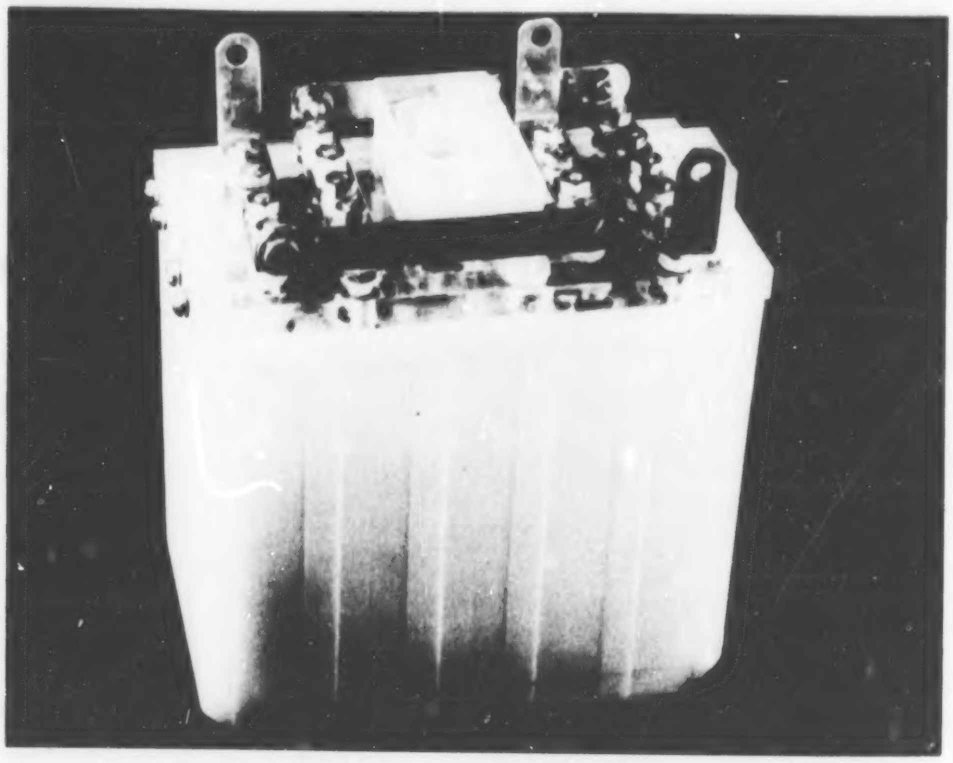


Figure 6. 60-watt, low-temperature, N_2H_4-O_2 oxygen cell (Electric Power Storage, Ltd.).

In Switzerland, Brown, Boveri Co., Ltd. is experimenting with low- and high-temperature systems that consume a variety of fuels, particularly methanol and hydrogen (Plust, 1966). Though primarily looking at low-output applications such as harbour buoys, TV repeater stations, and so on, the company has a high-performance H_2-O_2 unit of several hundred watts output. In Italy, the Fiat Company is also known to be experimenting with low-wattage units that consume hydrogen and to be looking at possible developments of electric automobiles.

SUMMARY

Several European Companies are exploring possible uses of fuel batteries for electric traction with the system generally chosen being the low-temperature hydrogen-oxygen (or air) cell. Although none of these developments has yet reached the stage where it could be adopted for passenger vehicles, they should supply data for proper feasibility studies in the near future.

Some of these systems could meet many of the requirements in the specifications in Table 2, but none could be made at a cost anywhere near the limit of £20 ($56) per kilowatt. Much of the capital cost of fuel cells is absorbed in the noble metal catalysts. Some progress is being made in reducing the amount necessary, but this is slow and the search for cheap alternatives that could be used with cheap low-grade fuels has not so far achieved a breakthrough. The materials of construction and other components also appear to make the cost prohibitive. Whether these problems can be solved will depend on the progress made during the next few years.

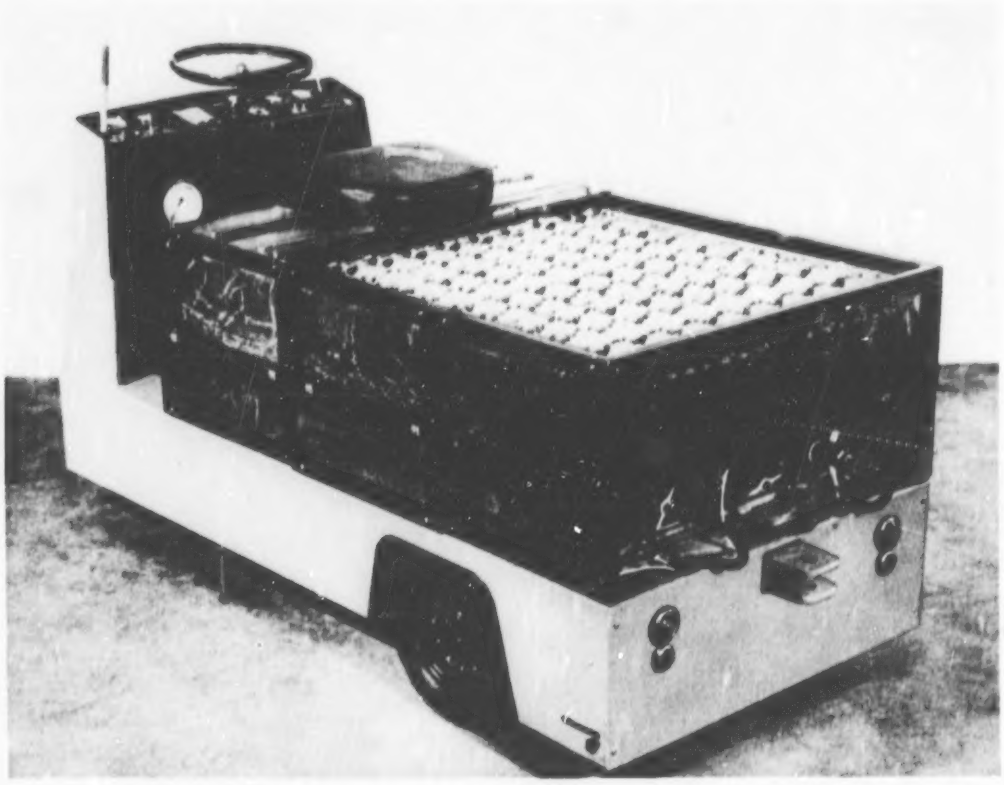


Figure 7. 2-kilowatt, hydrogen-oxygen low-temperature battery on an industrial truck (Electric Power Storage, Ltd.).

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AUXILIARY SYSTEMS: component development; other aspects of the total vehicle system.

Having worked with energy conversion and batteries since 1934, I am gratified to see the progress made in new and promising systems, either in production or in advanced stages of development. Before World War II the only secondary batteries were the lead-acid and nickel-iron in this country and lead-acid, nickel-cadmium, and nickel-iron in Europe.

At a time when a new urgent requirement for high-energy systems arises, many candidates are available thanks to the foresight of DOD and NASA in promoting very effective and far-reaching investigations of energy conversion systems from the beginning of World War II to the present time.

If similar efforts had been made on the rest of the components needed for the complete electric vehicle design, we would be much nearer to a matched power source and electric vehicle system.

We will go through a period of overdesign (larger power requirements) for the power source until a more efficient motor and control system are available. Thus, I strongly recommend that concentrated efforts be made to stimulate work in these other areas to bring them abreast of the power source effort.

I do not subscribe to the continuous complaint that the electric vehicle is impractical because of the lack of a suitable power source. This is true only because of the lack of development work on the rest of the components and systems required. A practical electric vehicle must be developed from the ground up as a system and not as individual components. We should not blame the power source for inefficiencies of the remainder of the system.

Although the power sources under development are not yet a final product, we can feel proud of the advances to date and the number of candidates available for design into the proper end product. With a little down-to-earth planning there is no reason why a successful system cannot be developed in the next 5 to 10 years.

Along with this development another major problem arises — educating the public to accept a practical electric vehicle regardless of appearance and limited performance. This effort may require as much time as developing the vehicle.

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ELECTRONIC CIRCUITS FOR SPEED CONTROL AND BRAKING

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New York, N.Y.

SUMMARY

Modern high-power semiconductors in comparatively simple circuits, controlling power from batteries that are capable of being recharged rapidly, make a battery-powered bus technologically practical for some urban applications. Regenerative braking can substantially extend the range between charges, in stop-and-go traffic, besides being a necessity for safety.

Some basic concepts of electronic circuitry incorporate "off-the-shelf" high-power semiconductors and 100-ampere-hour cells that can be charged at rates up to 1,000 amperes, for an operational bus.

INTRODUCTION

Experimental electric vehicles, operated with both batteries and fuel cells have been developed utilizing modern high-power semiconductors and power sources (SAE, 1967). David Ash (1967), a car-performance analyst, stated that the performance of some experimental cars compares favorably with that of conventional automobiles. An electric bus with electronic controls would give similar acceptable performance. High speed and long range between charges are not mandatory for a bus in urban traffic. A battery-operated delivery van would also be satisfactory in urban applications, because a van does not need high speed and long range. Hender (1965) reported that in Great Britain approximately 40,000 vehicles are battery-operated. The high cost of gasoline in Great Britain makes this particular factor of great importance, in addition to air pollution reduction. Since at present no major *economic* drive in the United States would encourage the use of battery-powered delivery vans, an initial political solution is probably most acceptable. For the introduction of battery-powered vehicles for reduction of air pollution, I suggest that we start with the battery-powered bus for the following reasons:

1. The bus is a much more obvious offender than a delivery van as contributor to air pollution because it is much larger and creates such obvious clouds of exhaust.
2. There are fewer buses than delivery vehicles.
3. The bus is generally public-owned, so the problem of initially higher cost should not be a major deterring factor.

4. The sense of community participation would be much greater with a bus, since so many people ride buses. Large numbers of citizens could experience pollution-free transportation, thus encouraging further expansion of battery-powered vehicles as better power sources are developed.

SPEED CONTROLS

The major objectives of electronic circuits for speed control and braking, in comparison with "conventional controls", are these:

1. Maximum utilization of stored energy for driving the vehicle, i.e., minimum power dissipation in the speed controls (for maximum range between battery charges).
2. Stepless speed control to simulate as closely as possible operation of the accelerator of a conventional vehicle (for acceptable vehicle performance).
3. Regenerative braking controls that will return energy to the batteries during the slowing-down of the vehicle (for further extension of vehicle range).

The objectives can be met by means of modern solid-state electronic circuitry. The degrees to which the objectives can be met are essentially governed by economics. Although the developmental costs of some automatic controls may be high, with advances in integrated and etched circuits techniques, the actual electronic logic circuitry can be cheap.

CONVENTIONAL CONTROLS

Figure 1 is a typical example of conventional controls, as used in the Henney Kilowatt. The batteries are switched from parallel to series-parallel to series arrangement by means of heavy-duty contractors. Also, the field winding of the motor is switched with paralleled and series resistance.

The electric motor in the "first generation" of electric vehicles can be a direct-current motor, "series" connected. The direct-current motor requires considerably fewer components and much simpler controls than an alternating current (SAE, 1967), and since this paper is confined to vehicles for urban use, which means short hauls and stop-and-go traffic, the increase in flexibility of performance possible with alternating current is not discussed. Further, the series direct-current motor is recognized as ideal for vehicles, because at low speeds its high torque can be used for rapid acceleration.

The control method of Figure 1 is a "lossless" speed control, (except for the lowest speed), because essentially all of the power coming from the battery goes into the motor. No power is dissipated in loss elements to control the speed. This system is not completely satisfactory, however. Besides the operational disadvantage of contactors switching heavy currents (currents above 500 amperes have been measured in performance of this car), which can result in rapid deterioration of the contacts in heavy stop-and-go traffic, the performance is jerky. Each time the system switches, the motor power changes rapidly, producing a discontinuous change of acceleration, or a jerk.

When being interrupted by a contactor, the currents develop microscopic amounts of ozone. The quantity is so small, that even if *all* internal combustion vehicles were changed overnight to electric vehicles with contactor controls, the increase in ozone concentration in urban areas would be scarcely detectable. Further, the use of electronic controls in any practical electric vehicle (see next section) would eliminate all ozone.

ELECTRONIC CONTROL

Figure 2 shows the basic circuit that can provide stepless power control. This circuit is known variously as "variable width pulse," "pulse width modulation", or "time ratio control." It is referred to herein as variable width pulse, or VWP.

In Figure 2, the source of power, assumed to be a battery, is permanently connected for maximum voltage output. A switch (S) is opened and closed rapidly to produce pulses of controlled width at the terminals (T) of the motor. Across the terminals of the motor is a diode (CR1), connected so that it does not conduct when the switch is closed. The series motor field is (F), the armature (A).

It can be shown (Wouk, 1962) that if the switching frequency of the switch (S) is high enough, then the motor will operate as though a steady direct-current voltage were applied to the terminals, the direct-current value being the average value of the voltage applied. This average is given by the equation:

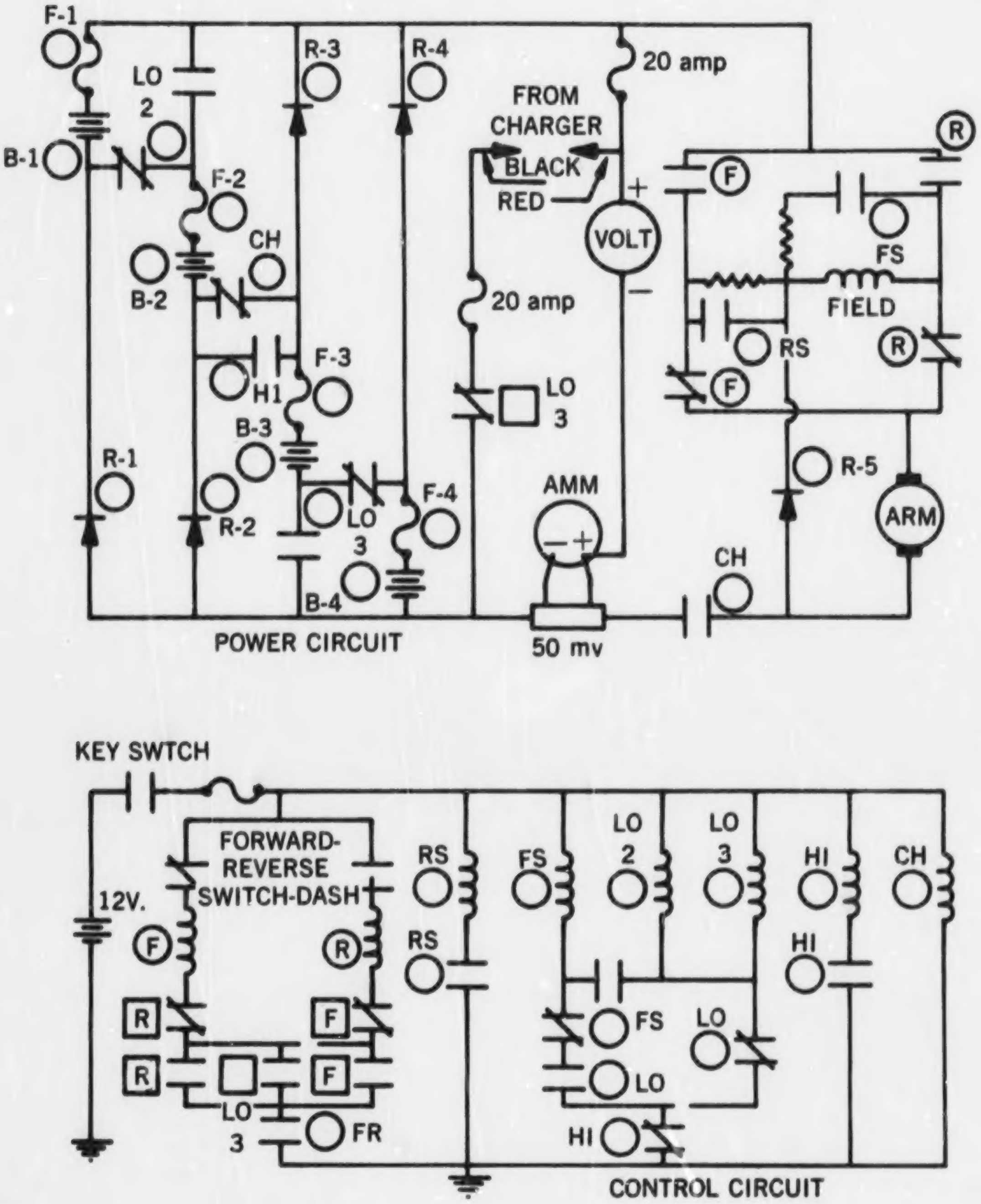
$$E_{out} = E_{in} \times \frac{t_1}{T} \qquad (1)$$

where

$t_{1,2}$ = time on (See Figure 3)
T = time between start of successive pulses.

With the switch closed for a short percentage of the total period, t_1 (Figure 3a), the equivalent voltage E_{out}, applied to the motor is low and the resulting speed is low. The current that is drawn depends upon the load on the motor. If the switch is closed for a longer portion of the period, t_2 (Figure 3b), the effective voltage applied to the motor terminals, is higher, and hence a greater speed is called for. The ratio of t/T is the "duty cycle."

If the switch (S) of Figure 2 is an electronic solid-state device, such as a thyristor (the generic term for an SCR or semiconductor-controlled rectifier), then it can be turned on and off with great


F-1
LO 2
R-3
R-4
20 amp
FROM CHARGER
BLACK
RED
B-1
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CH
B-2
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VOLT
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F
FS
FIELD
20 amp
H1
F-3
RS
R
F
LO 3
B-3
R-1
R-2
LO 3
F-4
AMM
R-5
ARM
CH
B-4
POWER CIRCUIT
50 mv
KEY SWTCH
FORWARD-REVERSE SWITCH-DASH
12V.
F
R
R
F
R
F
LO 3
FR
RS
RS
FS
LO 2
LO 3
HI
HI
CH
FS
LO
LO
HI
CONTROL CIRCUIT

NOTE:

☐ DENOTES CONTACTOR AUXILIARY SWITCH.

CONTROL CIRCUIT SWITCHES MARKED RS, FS, HI, FR, LO ARE CAM-ACTUATED.

KEY SWITCH OFF

Figure 1. Diagram of conventional controls.

rapidity, in the order of microseconds. (With a solid-state control, the current is interrupted and started with no arcing whatsoever, and accordingly no ozone is generated. Thus the ozone problem discussed earlier is completely academic.)

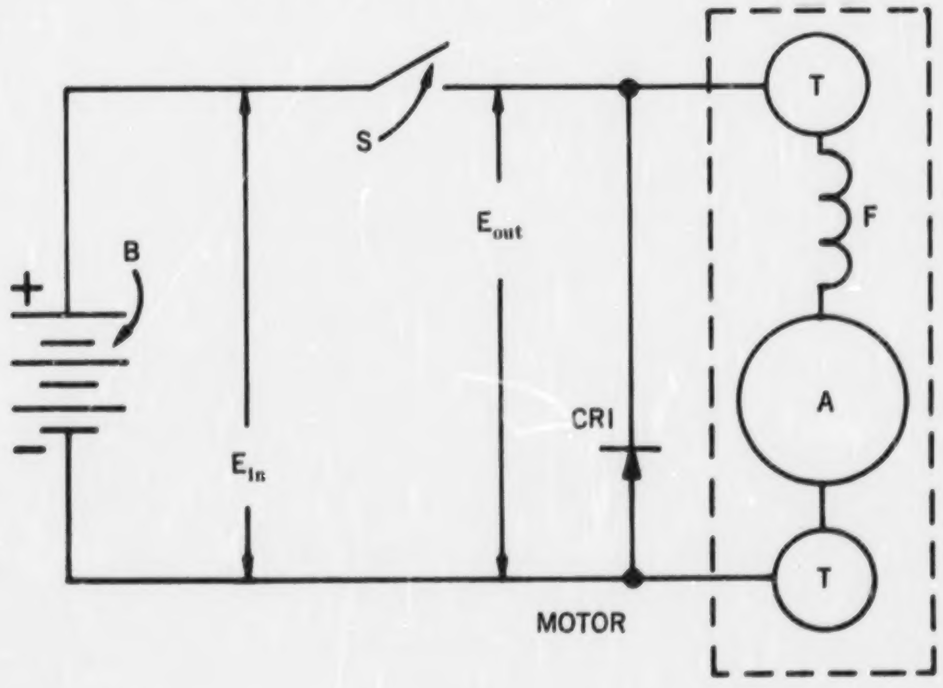

Figure 2. Basic variable-width pulse circuit for stepless, "lossless" direct-current motor control.

The function of the diode CR1 of Figure 2 is to bypass the motor current from the battery during the "switch off" interval. Without this diode, often called a free-wheeling diode, if the switch were to attempt to interrupt the current in the inductive circuit of the motor, high voltages would be generated that would vitiate the simplifying assumptions.

The circuit shown in Figure 2 can effect motor voltage control with no inherent power loss (except for unavoidable dissipation in the bypass diode CR1, and in the switch itself). Also, the following additional performance characteristics are readily obtainable with simple feedback controls.

Smooth Acceleration

Even if the accelerator were to be "floorboarded," i.e., depressed so as to demand virtually continuous conduction through the switch (S), the pulse width could be increased comparatively slowly to ensure gradual increase of voltage application to the motor.

This "gradual" could be over a period as short or as long as is desired, depending upon acceptable acceleration characteristics. It could be adjustable from the dashboard to give the vehicle a "jackrabbit" getaway characteristic, or a "little old lady" slow-acceleration characteristic (presently associated with electric-vehicle performance).

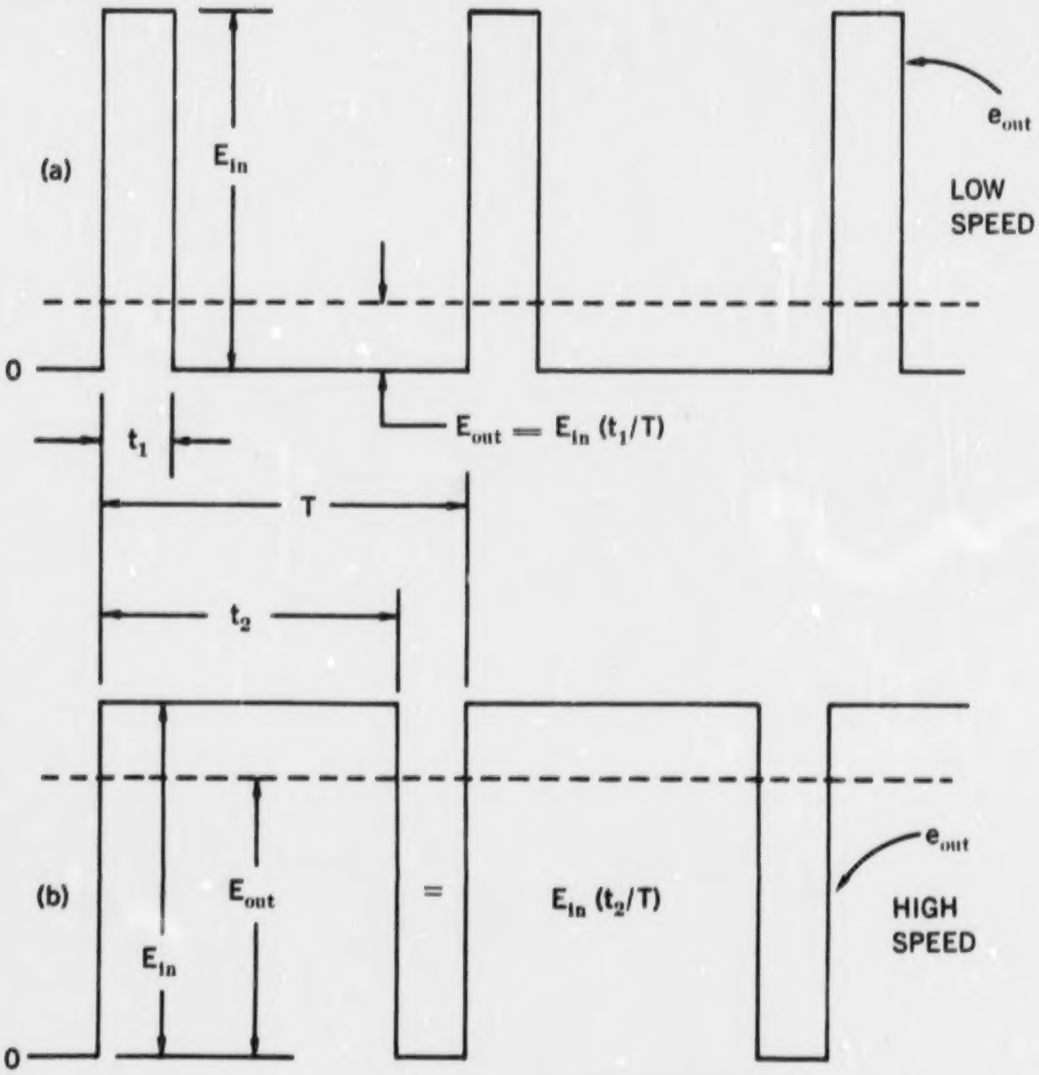

Figure 3. Waveforms of voltage applied to motor, low and high speeds.

Battery Current Limitation

Circuitry can be incorporated to limit the battery current, both for automobile performance control and for battery protection.

Thus, with a stalled motor (starting against locked wheels, etc.) the VWP could be maintained at a low value by circuits that would override the position of the accelerator and thus prevent damage to the control elements, the rectifiers, the motor brushes, or possibly the battery.

"Wild-Eyed Automation"

In principle, such an electronic control can be readily adopted to the "highway of the future" dream of completely automated and guided vehicles. Where starting or stopping a car or controlling a speed is a simple matter of electronic circuitry (not further linked to mechanical systems in the control), then a true over-all electronic control system can be effected with all its attendant possibilities of accurate response, automatic control, and other advantages.

Figure 4 shows the relative simplicity of the over-all controls. The speed-control circuits develop signals determined by the position of the tap on the potentiometer (R1), which represents the position of the accelerator pedal. The signal developed from this block determines when the power SCR will be turned off in the cycle shown in Figure 3.

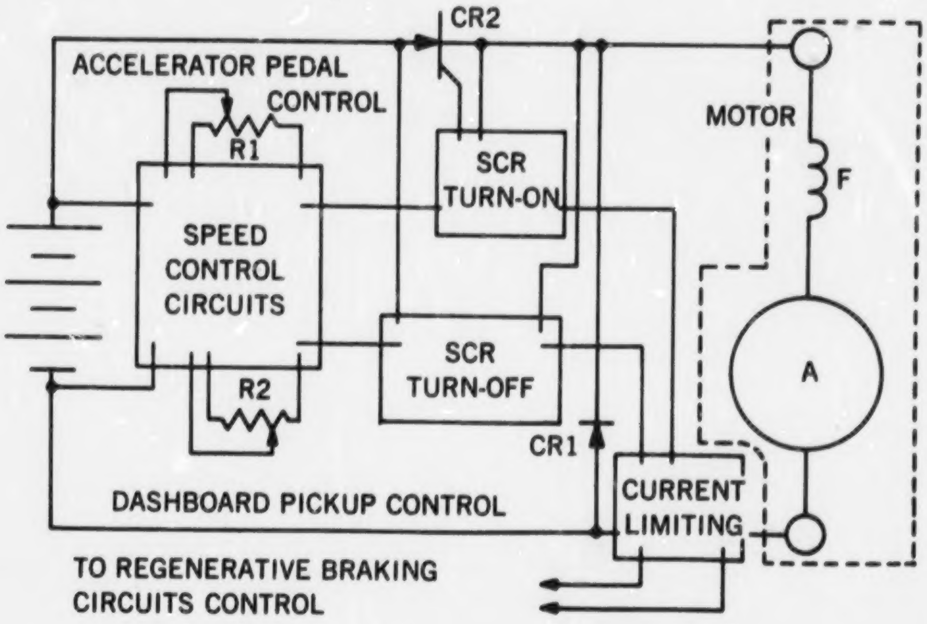
CR2
ACCELERATOR PEDAL
CONTROL
R1
MOTOR
F
SPEED
CONTROL
CIRCUITS
SCR
TURN-ON
SCR
TURN-OFF
A
R2
CR1
CURRENT
LIMITING
DASHBOARD PICKUP CONTROL
TO REGENERATIVE BRAKING
CIRCUITS CONTROL

Figure 4. Block diagram of control circuitry for full performance.

If the current becomes too great the current detection could override the speed-control circuit to limit the current. Further, if the pulse width has been reduced to minimum and the current is still excessive, then these circuits could decrease the pulse repetition rate.

POWER CIRCUITS

A feasible electronic power circuit is discussed here to illustrate basic cost considerations.

Data recorded on the Henney Kilowatt indicate that for acceptable performance under maximum load, such as going up a long steep hill, 500 amperes might be drawn from the battery (Private communication with C. Gold, Yardney Electric Corp, New York, N.Y.). Hence, the electronic controls would have to be designed for this "worst case." The 500 amperes are not delivered at full battery voltage, however, but at a lower voltage, 25 volts, corresponding to lower speed. Therefore, the duty cycle would be, let us say, 25 percent. Figure 5a shows the required motor current of 500 amperes. Figure 5b shows the applied motor voltage, assuming 100 volts from the battery, with 25 percent duty cycle. The average of this is 25 volts, which we are assuming corresponds to the voltage required to provide the needed current and hence power for the particular mode of operation.

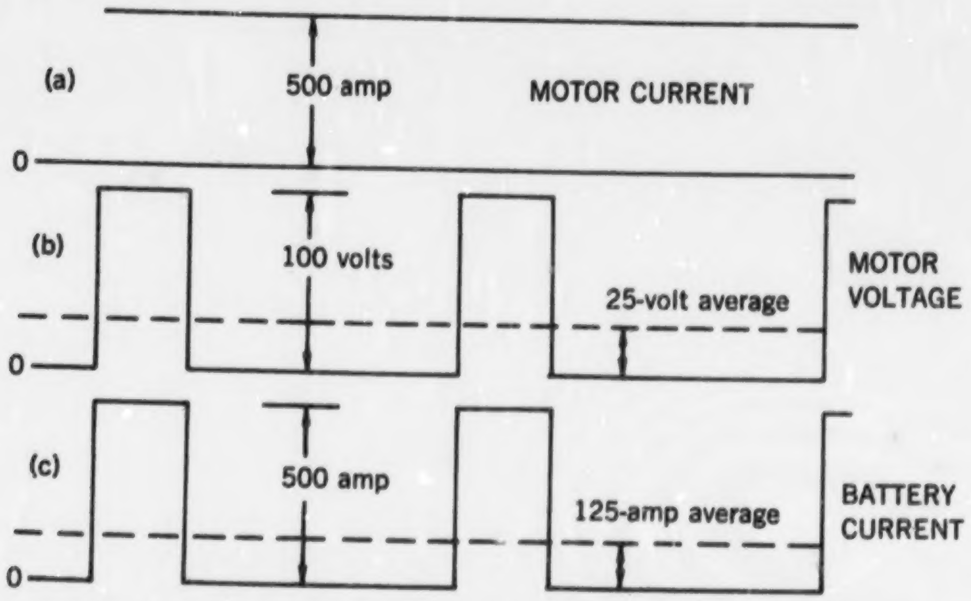

Figure 5. Voltage and current waveforms to illustrate 25 percent duty cycle.

Figure 5c shows the current through the power control switch. Although the average current flowing is 125 amperes, unfortunately, from an economic point of view, the heating and current ratings in these semiconductors depend to a large degree on root-mean-square (rms) values of current. In a pulse of this nature

$$I_{rms} = I_{peak} \sqrt{\text{duty cycle}}$$

So, the rms of this waveform is $500/\sqrt{4}$, or 250 amperes. For reliable design this is too close to the maximum rating available at present from a single inverter type of SCR. Hence, two SCR's would have to be paralleled.

If it were possible simply to parallel two SCR's, then each would handle approximately half the peak current, or 250 amperes, with each handling the rms current of 125 amperes, a safe value. Paralleling SCR's simply and reliably usually is done by dissipative methods

(Gutzwiller et al., 1964). A method of avoiding dissipation is to incorporate several SCR's, but operate them sequentially, as indicated in Figure 6, which shows a possible complete power control circuit. The rms currents would be 500/$\sqrt{8}$, or 178 amperes, a safe value. The explanation of the mode of operation is shown in Table 1. This is a "dissipationless" SCR turn-off method in that the energy in the capacitor is supplied to the load. Any losses are incidental, i.e., not inherent in the mode of operation. As components are improved, efficiencies will be improved.

Figure 7 illustrates some of the more important waveforms of voltage and current in such a circuit. The relationships are complex.

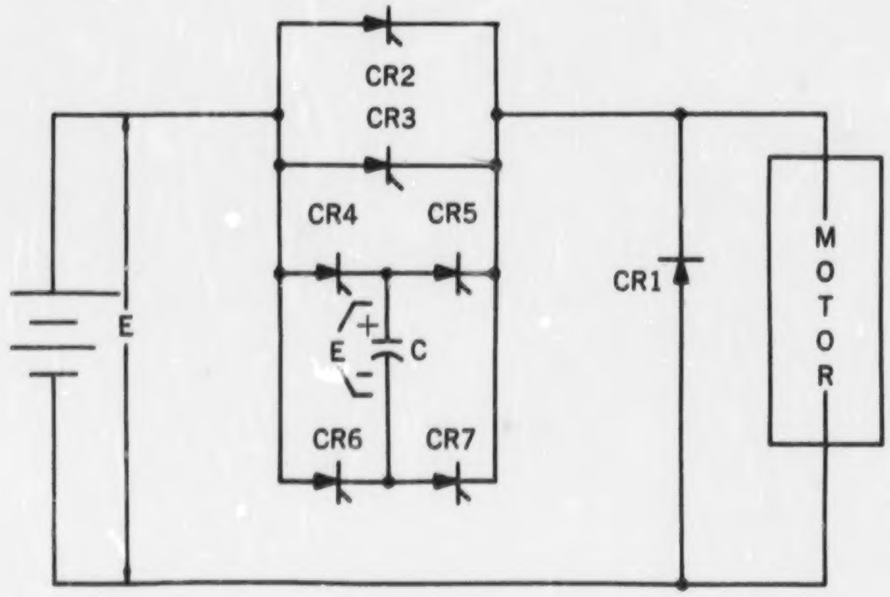

Figure 6. Circuit with sequential conduction of power SCR's for proper current rating.

Table 1. SCR's FIRING SEQUENCE and POWER CONTROL FUNCTIONS

Time	SCR(s) Firing	FUNCTION
t_0	CR2	Start application of power to motor.
t_1	CR5,6	Apply reverse voltage E to CR2. This blocks CR2, and commutates motor current to capacitor C.
t_2	NONE	C voltage reversed to E. All SCRs blocking. Motor current flowing through CR1.
t_3	CR3	Per CR2.
t_4	CR4,7	Per t_1, except CR3 blocked.
t_5	NONE	Per t_2.
t_6	CR2	Repeat cycle.

All waveforms are idealized. The motor current increases during the power pulse and decreases during a portion of the turn-off pulse and during the free-wheeling interval. Also, substantial switching transients of voltage and current usually occur. These are neglected for ease of understanding of the basic concepts.

All designations in Figure 7 are in accordance with IEEE standards. Lower-case letters denote instantaneous values. Upper-case letters denote average values, or rms values, as would be read by a meter. We will examine Figure 7 in detail, part by part.

(a) *The voltage applied to the motor.* During the horizontal portion parallel to the zero axis, voltage is applied through CR2 or 3. This persists for the interval t_1, which is adjustable for speed control. At the end of the interval, when the appropriate turn-off thyristors are fired (in this case CR5 and 6), initially the capacitor voltage adds to the battery voltage, so that the motor voltage is doubled. Since it is assumed that the motor current remains essentially constant during the entire interval, the voltage across the capacitor reverses at a constant rate, so that the voltage applied to the motor drops to zero linearly. It is this triangular position of the waveform that represents the "dissipationless" turn-off, in that the energy in the capacitor is supplied to the load.

(b) *The motor current.* The motor current is assumed constant.

(c) *The battery current.* Note that this current flows while either power thyristor is conducting and also during the interval that the turn-off-capacitor, voltage-applying SCR's are still conducting.

(d) *The current through one of the switching thyristors, in this case CR2.* Note that the current that flows is equal to the motor current, and it is assumed that the current turns off instantaneously when the turn-off thyristors are fired. Further note that the pulses occur ½ as frequently in (d) as they do in (c), because of the sequential firing previously discussed.

(e) *The current through the second power thyristor, CR3 in this case.* Note that the current is displaced one period of motor pulse frequency, T, but is otherwise identical.

(f) *The current through the turn-off thyristors CR6 and 5.* This current flows only during the interval following the turn-off of CR2. Its magnitude is equal to the motor current.

(g) *The current through the turn-off SCR's, CR4 and 7.* This current flows only after the turn-off of CR 3. Its magnitude is equal to the motor current, and it flows only during the capacitor voltage reversal interval. It is identical to (f), displaced by T.

(h) *The bypass diode current.* The current in CR1 flows only when all of the thyristors are extinguished and the voltage applied to the motor is essentially zero. The magnitude of current is equal to the motor current. The shorter the interval t_1, the greater will be the interval that CR1 conducts. It is further evident that the interval

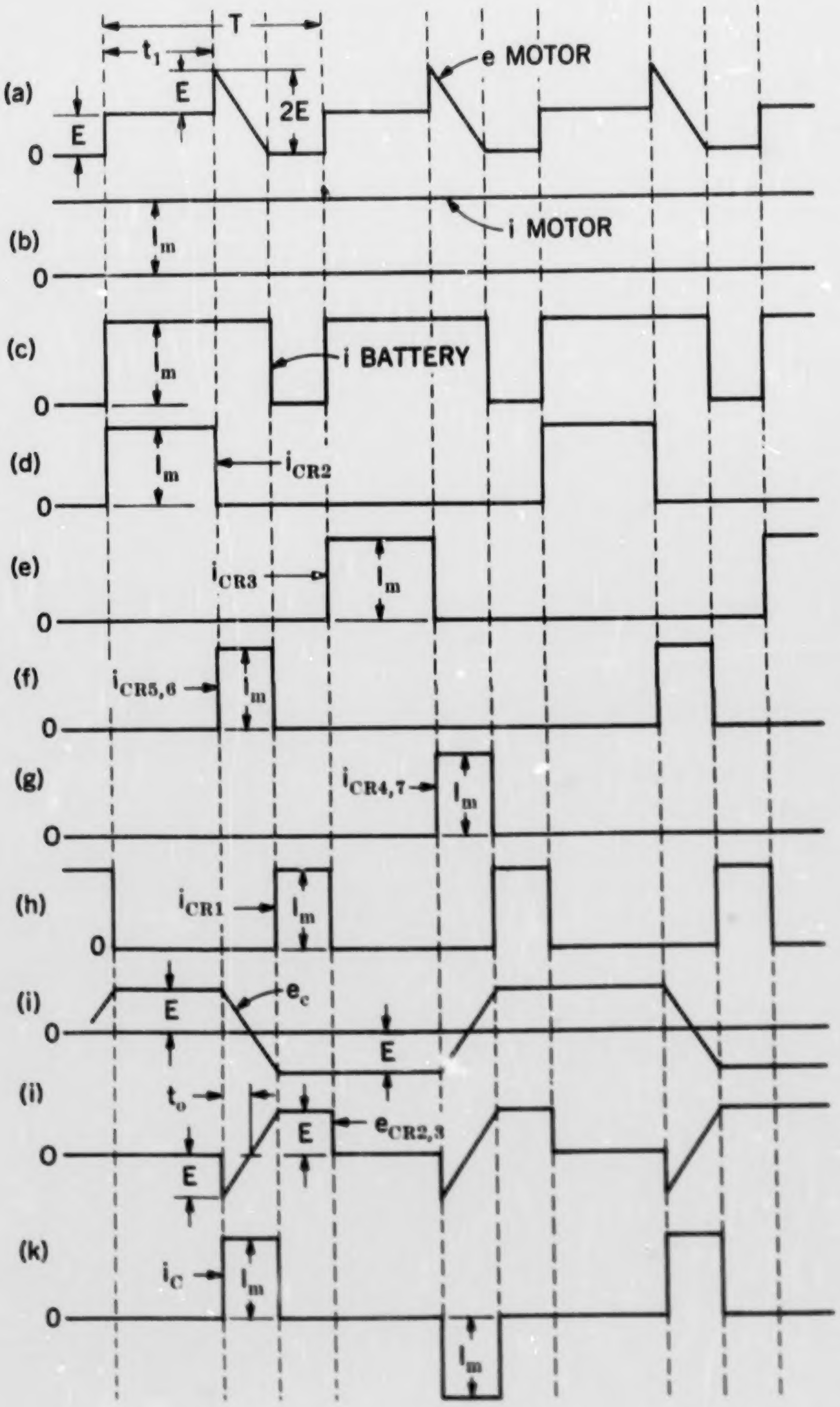
T
t1
E
2E
e MOTOR
(a)
E
0
i MOTOR
(b)
Im
0
(c)
Im
i BATTERY
0
(d)
Im
iCR2
0
(e)
iCR3
Im
0
(f)
iCR5,6
Im
0
(g)
iCR4,7
Im
0
(h)
iCR1
Im
0
(i)
E
ec
0
E
(i)
to
E
eCR2,3
0
E
(k)
iC
Im
0
Im

Figure 7. Basic waveform for circuit in Figure 6.

depends on the interval that the capacitor is conducting. These relationships are examined at length in Wouk (1962).

(i) *The voltage across the turn-off capacitor C.* Note the trapezoidal waveform, with the voltage essentially constant, either positive or negative, during the power interval and the free-wheeling interval. It changes linearly from one polarity to the other during the power thyristor turn-off interval.

(j) *The power thyristors CR2 and 3.* During conduction the voltage across *both* thyristors is essentially zero, even though only one of them is conducting. At turn-off, the voltage goes negative, because of the voltage across the capacitor, which initially is equal to the battery voltage. The voltage rises linearly from —E to +E, as the polarity of the capacitor is reversed. The interval between the time that the voltage initially goes negative and the time that it rises linearly again to zero, is known as the turn-off interval (t_o). The capacitance must be large enough to ensure that this interval is greater than some specified minimum (currently as low as 20 microseconds for inverter-type high-power thyristors). This interval of 20 microseconds, in conjunction with the maximum current that ever has to be turned off, determines the size of capacitor required by the relationship:

$$C = \frac{I_m}{E} \times t_o$$

This implies that with a light load, the "tail-off" will be longer. Since t_1 is usually correspondingly reduced, for an application such as this, it probably would never be necessary to modify the pulse repetition rate (T). This is analyzed at great length in Wouk (1962). During the free-wheeling interval, the voltage across the power thyristors is constant, equal to the battery voltage. Note that there are no *rapid rises*, or high rates of de/dt, in this circuit, which simplifies one of the design problems of employing thyristors, since no thyristor is subject to a rapid forward increase of voltage that might cause it to turn on spontaneously.

(k) *The current through the turn-off capacitor.* This current is alternating, with the rectagular peaks equal to the motor current and lasting during the turn-off interval of the power thyristors.

We emphasize that this circuit is only typical of many that may be developed; undoubtedly properly applied ingenuity will reduce the number of costly components without introducing other energy-dissipating elements. None of the engineering subtleties of circuitry, such as "softening" circuits or saturating reactors, are included in the circuit to reduce the di/dt through semiconductors.

At present such semiconductors are expensive. Using General Electric's type C185C for the power, type C55C for the commutating SCR's, and type A295B for the bypass diode would cost about $400 in large quantities.

REGENERATIVE BRAKING

In an urban vehicle, subject to frequent start-and-stop operation, with the slowing down time equalling an appreciable part of the accelerating time, a significant amount of power can be regained by the battery if the kinetic energy of the moving vehicle is returned by some reasonably efficient system into the batteries. Calculations of the watt-hours that could be returned to the battery in a bus slowing down from 30 mph to a halt are given at the end of this paper.

One of the reasons for the disfavor of regenerative braking in the past, as applied to battery-powered vehicles, undoubtedly has been the enormous regenerative braking currents. Batteries that normally could have accepted such rates of recharge would have required substantial overdesign for normal operations. With the availability of high-speed recharge nickel-cadmium cells, regenerative braking now becomes practical for a battery-operated bus.

The calculations are completely theoretical and assume no losses whatsover. Even if the losses in the regenerative braking process reduce the actual range of extension, regenerative braking offers important advantages above and beyond range extension.

One of the advantages is safety of operation. Existing battery-powered vehicles give the driver free-wheeling on straightaways, which may not be undesirable, except for the uneasy feeling it may give the driver that he has no control over the car. Down steep grades, however, the problem of brake failure is a serious one, and the braking action of regenerative braking adds an important dimension to driving safety. It acts as a safety device in slowing down the car, and in addition to the incidental advantage of recharging the batteries, it also lessens wear and tear on the brakes.

Figure 8 shows the basic connections required for regenerative braking. An additional component is required, in this case shown as CR2, to conduct the power from the armature of the motor back to the battery.

As indicated briefly before, the circuit of Figure 6 is indeed in free-wheeling through CR1, when all SCR's are open, corresponding to the foot off the accelerator. The current that may have existed when the foot was removed from the accelerator would decay to zero, because of circuit losses in the circuit that consists of the three basic elements — the armature, the field coil, and the diode. A very slight braking action is not even possible, because without the field being reversed, the motor could not act as a generator. To be a generator, the current would have to flow out of the terminals as shown, rather than into them, and the current could not flow in this direction through the diode.

Figure 8 shows how motor braking can be introduced, under the assumption that to minimize maintenance problems the design objective prohibits the use of contactors. For the motor to act as a generator, the series field would have to be reversed. Since this is assumed undesirable, an additional field coil, which could be a shunt field, would be employed. Current could then flow as shown from the armature through CR2 into the battery, recharging the battery.

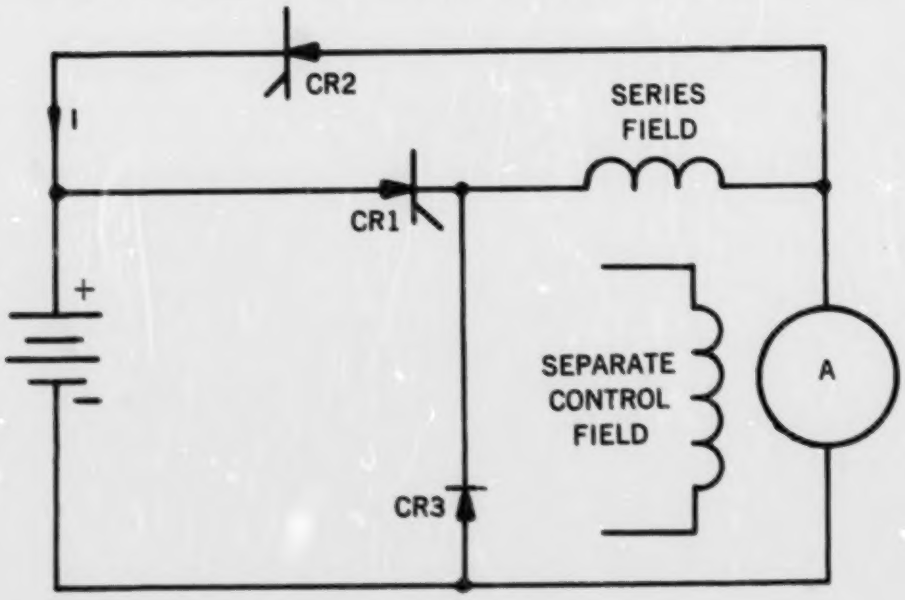

Figure 8. Basic connections for regenerative braking.

The amount of current flowing back into the battery is given by

$$I = \frac{E_g - E_{CR2} - E_b}{R} \tag{2}$$

where

E_g = the voltage generated by the motor, now acting as a generator.

E_{CR2} = the voltage across CR2.

E_b = the battery voltage.

R = the sum of all circuit resistance, including internal resistance of the battery, the generator, and the wiring.

The generated voltage is shown by

$$E_g = k\,\Phi\,w \tag{3}$$

where

k = a constant.

Φ = the flux density in the control field.

w = angular velocity of the armature, which is directly proportional to car speed. Therefore equation (3) can be rewritten

$$E_g = k\Phi v \tag{4}$$

As the vehicle slows down, if all other parameters are held constant, the generated voltage will drop and the feedback power will drop, causing the braking effect to be reduced. This action is contrary to present operating experience. Because mechanical brakes are usually Coulomb braking, i.e., constant braking force (within limits), the field strength (Φ) must be increased as the speed decreases, until it is impractical to increase the field strength further to compensate for the lower velocity.

The foregoing implies indirectly, and it should be stated here directly, that *regenerative braking cannot bring the vehicle to rest.* The function of regenerative braking is to return as much energy as possible to the battery, not to stop the car. The brake pedal will therefore be somewhat more complicated in overall function than at present. For the start of brake travel, the regenerative braking will take place, but as the car reaches some minimum speed the braking force will be eliminated by the motor and the operator will have to depress the pedal farther to put mechanical braking into effect. Since the kinetic energy is proportional to the square of the velocity, reducing the speed to ¼ initial value will absorb 90 percent of the initial energy.

Here again the electronics will lend themselves readily to automatic control. Depending upon pedal pressure, the field strength could be controlled automatically to maintain constant current into the battery independent of speed, with mechanical feedback to simulate present operation of the foot pedal.

Figure 9 shows a possible implementation of such a circuit. CR1 and CR2 are the power control SCR and the bypass diode, respectively, for normal-drive operation; these are assumed inoperative when the driver's foot is off the accelerator. If the brake pedal is depressed, the rheostat shown will be activated by hydraulic pressure and will turn on the transistor through the transistor control circuits. These in turn will apply current to the shunt field, which generates a voltage at armature terminals 1 and 2. Simultaneously CR3 is turned on as the voltage is generated at the armature terminals, developing a voltage higher than the battery voltage. When the SCR fires, current flows into the battery at a rate determined by equation (2).

The current can be detected by the same or a different current detecting circuit mentioned with respect to Figure 4. In all events this current can be maintained constant by automatic circuits, which will control the current through Q1 and hence the current into the shunt field coil, which in turn determines the battery current that will flow. As the motor slows down, the transistor can be driven further into conduction.

As a final example of the value of regenerative braking and the magnitudes of current involved, Figure 10 shows some of the parameters of a 3,000-pound vehicle being held to a 10-mph speed on a 10 percent grade, with 100 volts of batteries being recharged

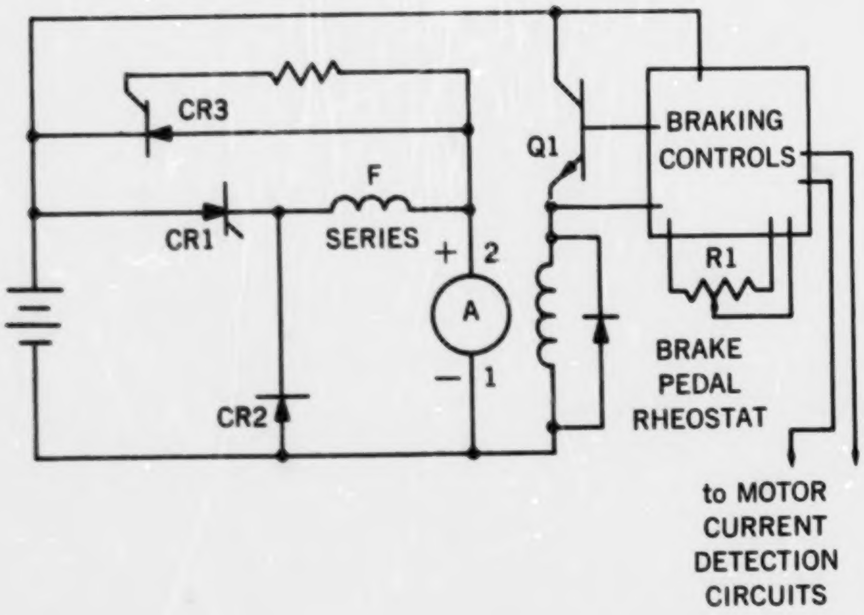
CR3
Q1
BRAKING
CONTROLS
F
CR1
SERIES
+
2
A
−
1
R1
BRAKE
PEDAL
RHEOSTAT
CR2
to MOTOR
CURRENT
DETECTION
CIRCUITS

Figure 9. Circuit diagram for controlled regenerative braking.

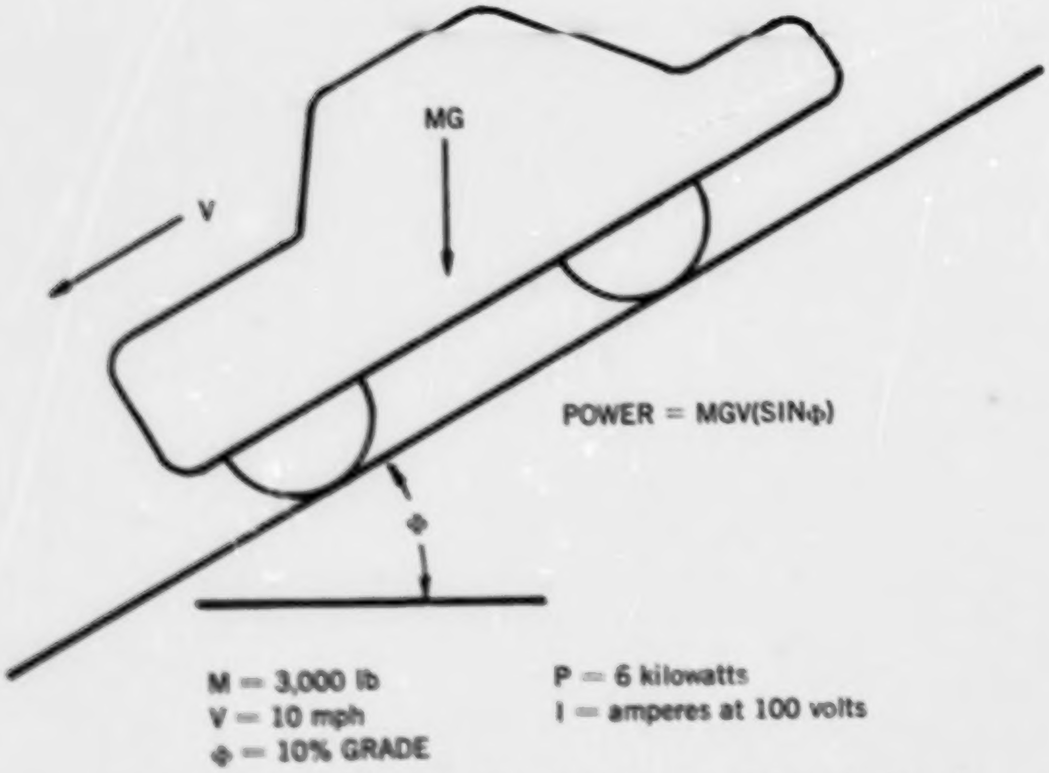
MG
V
POWER = MGV(SINφ)
φ
M = 3,000 lb
V = 10 mph
φ = 10% GRADE
P = 6 kilowatts
I = amperes at 100 volts

Figure 10. Regenerative braking requirements of automobile on downgrade.

through regenerative braking. The recharging current would be approximately 60 amperes.

For a 30,000-pound bus under similar circumstances, with 300 volts worth of battery, the recharging current would be 200 amperes.

These figures indicate why, for practical applications in a battery-powered vehicle, "dynamic braking," where the power is sent into a resistor (which would allow braking action down to much lower speeds), is impractical. On a 1-mile grade, for example, where the resistors would be absorbing power for 6 minutes, the resistor bank would have to be disproportionately large to absorb and dissipate the energy properly.

CONCLUSION

In a battery-powered vehicle, electronic circuits can perform the functions of electric motor control for maximum utilization of battery power and can provide performance similar to that of conventional fuel engines. In addition, electronic controls can allow regenerative braking, which will provide performance similar in most respects to conventional braking on conventional automobiles. The circuits that will obviously work at present, even in quantities of thousands, will be substantially more expensive than the simple mechanical controls for a conventional automobile. However, if we apply the lower prices of low-power semiconductors, the outlook is much more attractive. In an application such as a bus, where the complete elimination of the contribution to air pollution is invaluable to the community, the added initial cost of the battery-powered bus is negligible.

The possibility of polluting the air with ozone, discussed earlier, is purely academic when semiconductors are used. Some people have also shown concern about the strain on the electric-power-generating capacity of the United States if battery-powered vehicles were used widely. This concern is completely unnecessary, because if all internal combustion engines were converted to battery-powered vehicles overnight, the load requirements on the electric utilities would be approximately doubled. Calculations of power-generation are also given at the end of this paper.

All facets of the air pollution problem point to the great desirability of putting into operation at once, with today's technology, a battery-powered bus. When tomorrow's technology eliminates the problems of range, speed, and initial cost of battery-powered buses, we will all be able to enjoy the benefits of this pollution-free type of transportation.

CALCULATIONS OF POSSIBLE EXTENSION OF RANGE BETWEEN CHARGES WITH REGENERATIVE BRAKING

Data recorded on the Henney Kilowatt indicate that a car with four passengers running on a level at 30 mph draws approximately

60 amperes at 40 volts (Private communication with C. Gold, Yardney Electric Corp, New York, N. Y.). (100 volts of 100-ampere-hour cells are used.) This represents a drain of 2.5 kilowatts, with a load of 2,600 pounds, car and passengers.

For a bus with 10 times the number of passengers, assume 10 times the total weight, and 10 times the "road load", or 25 kilowatts; to keep the "steady" current below 100 amperes, use 300-volt batteries.

Then

$$\text{Mass of bus} = m = \frac{26{,}000 \text{ lb}}{2.205 \text{ lb/kg}} = 11.8 \times 10^3 \text{ kg}$$

At 30 mph,

$$v = \underset{(\text{mph})}{30} \times \underset{(\text{ft/sec/mph})}{1.4667} \times \underset{(\text{meters/ft})}{0.3048} = 13.4 \text{ mps}$$

From National Safety Council charts, the safe stopping distance at 30 mph is 90 feet.

$$90 \text{ feet} = 90 \times 0.3048 = 27.43 \text{ meters}$$

Assuming constant braking effect, so speed reduces linearly to zero,

$$\text{average velocity} = \frac{13.4}{2} = 6.7 \text{ mps}$$

$$\text{time to come to stop } T = \frac{27.43}{6.7} = 4.1 \text{ seconds}$$

$$\text{Initial bus kinetic energy} = 0.5\, mv^2$$
$$= 0.5 \times (11.8 \times 10^3) \times (13.4)^2 = 1.05 \times 10^6 \text{ joules}$$

If all of this energy were fed back to the battery by bringing bus to a halt, then

$$1.05 \times 10^6 = EIT$$

where

E = battery voltage, assumed 300 volts for a large bus

T = 4.1 seconds

$$I = \frac{1.05 \times 10^6}{4.1 \times 300} = 850 \text{ amperes}$$

Thus, the required value of current for successful regenerative braking is well within the range that some nickel-cadmium batteries can absorb.

The energy absorbed during stopping, approximately 10^6 joules, will drive the bus, at the assumed 25-kilowatt drain, for a time

$$t = \frac{10^6}{25 \times 10^3} = 40 \text{ seconds, or}$$

a distance of

$$\frac{40}{60} \times \frac{1}{2} = \frac{1}{3} \text{ mile, at 30 mph.}$$

The assumed battery capacity of 300 volts, 100 ampere-hours, will run the bus continuously for approximately

$$\frac{300 \times 100}{25 \times 10^3} = 1 \text{ hr at 30 mph}$$

In an urban area such as congested midtown Manhattan, this distance (30 miles) is more than adequate. Regenerative braking, which may extend the range by 25 to 50 percent, renders the battery bus concept even more practical.

CALCULATIONS OF ELECTRICAL-POWER-GENERATING CAPACITY REQUIRED FOR INSTANT CONVERSION OF ALL CONVENTIONAL VEHICLES TO ELECTRIC DRIVE

The following figures are based on approximate parameters in a region such as New York State and are rounded off for ease of calculations.

(1) Assume number of vehicles $= 10{,}000{,}000 = 10^7$
This value is the correct order of magnitude for New York State.

(2) Assume horsepower per vehicle $= 250$.
A reasonable assumption; horsepower of buses and trucks, is higher, and of many small cars, lower.

(3) From (2), kilowatts per vehicle $= 250 \times 0.746 = 200$ kilowatts

(4) Assume present electrical-power-generating capacity in New York State $= 20{,}000{,}000 = 20 \times 10^6$ kilowatts.

This value is fairly close to the actual figure.

At first glance, it might appear as though the additional power required is indeed formidable. From (1) and (2), the additional capacity needed =

(5) 200 (kilowatts per vehicle) $\times 10^7$ (vehicles) $= 200 \times 10^7$ kilowatts

From (4) and (5) the additional power required is

(6) $(5)/(4) = 200 \times 10^7 / 20 \times 10^6 = 100$

i.e., the generating capacity would have to be increased 100-fold.

This figure looks formidable and has been quoted in newspapers; however, this reasoning incorporates two major fallacies.

FALLACY 1:

The 200-kilowatt power figure of equation (3) is *peak* power, used only infrequently, when the vehicle accelerates rapidly or moves up steep inclines. The *average* power required is substantially less.

Taking into account the lower average power requirement, plus the acknowledged greater efficiency of a battery-electric motor system, one might estimate the average power requirement at 20 kilowatts. So, from (6):

$$(7)\quad 100 \times \frac{20\ \text{kw}}{200\ \text{kw}} = 10, \text{ or a tenfold increase.}$$

The tenfold increase is still substantial.

FALLACY 2:

Vehicles are NOT used 24 hours a day. Considering values from 24 hours a day for some taxis to 2 hours a week for some suburban cars, we can reasonably estimate an average use of 2.4 hours a day. Using (6) and (7) and 2.4 hours, we get

$$(8)\quad 100 \times \frac{20\ \text{kw}}{200\ \text{kw}} \times \frac{2.4\ \text{hr}}{24\ \text{hr}} = 1$$

i.e., the order of magnitude of increased electrical power required is a doubling, not a 100-fold, multiplication.

The recharging process for batteries is not distributed uniformly during the day. If we assume the worst, that all vehicles are plugged in at the same time and recharged in 8 hours, then the value in equation (8) would be tripled.

Nobody expects electric vehicles to replace internal combustion engines overnight. More probably, where battery-powered vehicles are brought into use, the changeover will take place in 10 to 20 years. The electric utilities can readily absorb, with their anticipated normal expansion, the additional capacity needed for battery-powered vehicles.

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THE MECHANICAL DESIGN OF ELECTRIC AUTOMOBILES

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It is not necessary that the mechanical design of electric cars differ from that of conventional automobiles. Indeed, many of the electric cars that have been built have substituted an electric prime mover for the gasoline power plant in an otherwise conventional vehicle. There is the feeling, however, that totally new designs might provide better electric vehicles than can modifications of standard vehicular designs.

One difficulty of the electric vehicle is that batteries plus electric motors are costly and heavy in comparison to the gasoline engines that can do similar jobs. There has been no competition. In its technical performance as a torque producer, the gasoline engine is far ahead of any prospective challengers. If, however, a valid reason exists for considering electric motive sources, we have no good reason not to exploit any mechanical design possibilities inherent in the new power source.

For vehicular elements other than the power source, there is no need for complete redesigning. An electric automobile would embody the same components, except for the propulsive elements, found in conventional cars — but they may look different, be made from different materials, and such. We are fortunate that automotive technology endows us with a rich art from which to draw know-how appropriate to our purpose.

Somewhat aside from the internal engineering aspects are mechanical design factors relating to the marketing and use of electric cars. At the present stage it is well to take these factors into account, since they have a quite significant part in the decision whether or not to design and build electric cars at all. Part of our purpose here is to construct images of clearly desirable and useful automotive transportation systems that are consistent with technological capabilities and economic realities.

ELECTRIC VERSUS CONVENTIONAL CARS

Electric vehicles can be superb machines. The persistent problem that must be reconciled in all electromotive designs, however — that of storing sufficient energy in a less-than-enormous package and at a cost that can be afforded — is the battery problem. It dominates even the mechanical design of electric vehicles. Except for this problem, wholly satisfactory electric vehicles could be made by merely replacing the engines of conventional cars with electric motors and batteries.

The conventional gasoline-powered car is the standard against which electric vehicles will inevitably be compared. Modern automobiles typically have weight-to-power ratios on the order of 20 pounds per road horsepower. Reid (1966) shows, on the basis of published figures, that contemporary cars have weight-to-power ratios of about 10.9 pounds per horsepower. This figure is degraded to around 20 when "road" horsepower is considered.

These numbers are significant in assessing the broad potential of electric cars. For example, 20 pounds per horsepower is a typical weight for electric motors of standard design and construction. Thus, it is practically obvious that, barring radically improved motors, an electric car even without batteries could not match the performance of a conventional automobile. The energy-to-weight ratio of modern cars, 80 watt-hours per pound — and that is for the entire car — is better than the energy density of even the superior silver-zinc batteries. If, then, by some miracle one could effect propulsion from a battery alone, sans car, the machine still would not be attractive on the basis of energy density. Because of the low energy density, the range of electric vehicles will necessarily be limited.

AUTOMOTIVE ENERGIES

Power must be provided in an automobile for both propulsion and accessories. In general, propulsion power is applied to raise the kinetic and potential energies of the car and to overcome frictional and drag forces. The stored energies are potentially recoverable, but energy applied to overcome frictional and drag forces or to operate accessories is not. The distribution of automotive energies is considered in the following paragraphs.

Modern low-profile, low-pressure tires allow a comfortable ride and good handling, but they consume a significant amount of energy. Tire rolling resistance is a function of a number of parameters, including specific tire design, materials of construction, tire diameter, car weight, and vehicle speed.

Table 1. ENERGY LOSS IN TIRES[a]

Tire rolling resistance coefficient, lb/lb	WEIGHT, lb			
	1,000	2,000	3,000	4,000
	kw-h/mile			
0.008	0.016	0.032	0.048	0.064
0.010	0.020	0.040	0.060	0.080
0.012	0.024	0.048	0.072	0.096
0.014	0.028	0.056	0.084	0.112
0.016	0.032	0.064	0.092	0.128

[a] From Campbell and Hunsberger, 1962.

Table 1 shows the approximate energy requirement, in kilowatt-hours per mile, to overcome tire rolling resistance for variations in car weight and in the tire rolling resistance coefficient. The typical modern car requires nearly 0.1 kilowatt-hour per mile to overcome tire rolling resistance.

Table 2. ENERGY LOSS DUE TO AERODYNAMIC DRAG[a]
(at constant 35 mph)

Air resistance coefficient, lb-hr^2/(ft-mile)^2	FRONTAL AREA, ft^2			
	15	20	25	30
	kw-h/mile			
0.0006	0.022	0.029	0.035	0.046
0.0008	0.029	0.039	0.047	0.059
0.0010	0.037	0.049	0.059	0.074
0.0012	0.044	0.059	0.071	0.088
0.0014	0.051	0.069	0.082	0.103

[a] From Campbell and Hunsberger, 1962.

Energy is also consumed by aerodynamic resistance. Table 2 shows these energy losses for variations in drag coefficient and in the frontal area of the car. Of course, aerodynamic drag is strongly dependent on speed. Table 3 shows the effect of speed on the aerodynamic losses of the typical modern car. For the typical car, aerodynamic losses predominate over other losses at speeds of about 45 mph and greater.

Table 3. ENERGY LOSS DUE TO AERODYNAMIC DRAG[a]

Speed, mph	Energy Loss, kw-h/mile[b]
10	0.005
20	0.019
30	0.048
40	0.077
50	0.120
60	0.173
70	0.235
80	0.307

[a] From Campbell and Hunsberger, 1962.

[b] Aerodynamic drag coefficient of 0.0012 and frontal area of 20 ft^2 are assumed.

The energy required for acceleration increases the kinetic energy of the vehicle so that, in principle at least, some fraction of that energy could be recovered. Table 4 shows the energy amounts required to accelerate vehicles of various weights to certain speeds.

Table 4. ENERGY REQUIRED FOR ACCELERATON

Vehicle speed, mph	VEHICLE WEIGHT, lb			
	1,000	2,000	3,000	4,000
	kw-h/mile			
20	0.010	0.020	0.030	0.040
40	0.040	0.080	0.120	0.160
60	0.090	0.180	0.270	0.360
80	0.160	0.320	0.480	0.640

Energy is also required for hill-climbing. Although in the long run the car will descend as many hills as it climbs, the potential energy gained during an ascent may be partly lost through braking when descending. Table 5 illustrates the effect of grade on energy expenditure.

Table 5. ENERGY REQUIREMENTS DUE TO GRADE

Grade, %	VEHICLE WEIGHT, lb			
	1,000	2,000	3,000	4,000
	kw-h			
−2	−0.040	−0.080	−0.120	−0.160
0				
+2	+0.040	+0.080	+0.120	+0.160
+4	+0.080	+0.160	+0.240	+0.320
+6	+0.012	+0.240	+0.360	+0.480

Requirements for accessory power can vary widely, from a few watts to several kilowatts. On the basis of current practice, heating and cooling are the major items in the energy budget for accessories. Accessories such as lighting or convenience features normally require only small amounts of energy.

It is not unusual for automobile heaters to have outputs of 20,000 or 30,000 Btu per hour, the equivalent of about 6 or 8 kilowatts of electrical resistance heating. Automotive air conditioners often can pump about 20,000 Btu per hour. In line with electrical air conditioning practice this output would require about 3 kilowatts of power. It is easy to see that even a low-powered electric air conditioner can consume considerable energy.

The requirements for heating would perhaps best be met by using a non-battery-powered source, e.g., a phase-change system that could be "recharged" by resistance heating when the batteries are being charged. One of the best phase-change systems, although somewhat exotic, is the lithium hydride system. Lithium hydride releases about 1000 Btu per pound upon freezing. A practical lithium hydride "heat cell" might easily produce more than 350 Btu per pound, or approximately 100 thermal watt-hours per pound. Chemically fueled heaters could provide even more heat per unit weight, although the air pollution problem would have to be reckoned with. Catalytic heaters that "burn" fuel at low temperatures are, however, reputedly free of noxious effluents.

TOTAL ENERGY REQUIREMENTS

Total energy requirements for various driving modes are examined in Table 6. Three types of driving are considered.

Urban — average speed 15 mph; 5 stops per mile

Suburban — average speed 30 mph; 1 stop per mile

Turnpike — average speed 60 mph; 0.01 stop per mile.

Table 6. ENERGY REQUIREMENTS OF A TYPICAL MEDIUM-SIZE AMERICAN CAR FOR VARIOUS TYPES OF DRIVING
(kw-h/mile)

Energy use	Urban	Suburban	Turnpike
Tires	0.092	0.092	0.092
Aerodynamic losses	0.011	0.048	0.173
Acceleration	0.086	0.053	0.003
Total	0.189	0.193	0.268

The totals in Table 6 are approximations of the energy requirements for propulsion. The requirements may be somewhat understated in that they exclude allowances for system inefficiences and for powering accessories. A "worst-case" accessory load might include an air conditioner operating at 10,000 Btu per hour and requiring about 1,700 watts; with other small loads, the total accessory load could be 2 kilowatts. In the case considered, then, the energy requirements would be as shown in Table 7. Reid (1966) determined that modern cars expend energy at a rate of about 0.3 kilowatt-hour per ton-mile. For a 3,000-pound car, 0.45 kilowatt-hour per mile would be the corresponding expenditure rate. This figure seems to agree well with the numbers derived here for idealized situations.

Table 7. TOTAL ENERGY REQUIREMENTS OF ELECTRIC VEHICLE DURING VARIOUS DRIVING MODES
(kw-h/mile)

Load totals	Urban	Suburban	Turnpike
Propulsion	0.189	0.193	0.268
Accessories	0.133	0.067	0.033
Propulsion plus accessories	0.322	0.260	0.301

What were the energy requirements of early electric cars? J. E. Homan (1911) wrote: "The current consumption of electric vehicles operated by storage batteries varies more or less with different makes, but some idea of the same may be obtained from the results of a test run of 62 miles over dirty and slippery roads recently made in France. In this run a number of electric vehicles each carrying four passengers and weighing, complete, over 2 tons, covered the entire distance at an average speed of 15 miles per hour with an energy consumption of about 160 watt-hours per ton mile. The best performance was that of a Vedrine, which required 133 watt-hours per ton mile. Under ordinary conditions, this vehicle consumes 110 to 120 watt-hours per ton mile."

Although many changes have taken place since that early day, it appears that the 0.180 kilowatt-hour per mile that would have been required by a 3,000-pound vehicle is slightly less than would be required by a present-day vehicle operating under similar conditions.

Consideration of data in Tables 6 and 7 in light of current battery art tells us plainly that practical battery-powered turnpike vehicles are not in the immediate offing. For urban-suburban driving, where long range is not required, strong technical promise for practical electric vehicles is implied — even for off-the-shelf components. However, since the power system in a vehicle built with available elements falls far short of the standard to which we are accustomed, promising directions for further development should be examined.

INCENTIVES FOR IMPROVED DESIGN

The power source is the only part of the conventional automobile that is inherently different from an electric car. The motor and, in particular, the ponderous batteries of electric vehicles have led many to expound the need for lighter weight, more powerful motors and batteries. Better batteries and motors are, of course, much to be desired. However, other directions for development that lie within the area of mechanical design could be at least as rewarding and perhaps more immediately productive.

Other approaches can be illustrated by analogy in the aphorism, "One can either make more than he spends or spend less than he makes." That is, improving the efficiency of propulsion may be as fruitful a course to pursue as that of developing batteries that have higher energy density.

For example, we have considerable incentive for seeking tires with lower rolling resistance coefficients. Tire rolling resistance is a major energy loss during propulsion. For the automotive racing world, tire manufacturers have recently performed some minor miracles in designing and constructing high-performance racing tires. Perhaps, if given the challenge, tire manufacturers could develop a tire with very low rolling resistance for electric vehicle service. Also, light weight is desirable to reduce tire rolling drag losses and energy requirements for acceleration and hill-climbing. Although there is a large incentive for a lightweight vehicle, we are cautioned by Homan, who wrote, 56 years ago: "There may be some advantages in light constructions, formerly supposed to be essential, but present-day practice recognizes the evident fact that strength and durability are more important considerations."

Nevertheless, light weight does afford a technically more efficient machine. Eliminating a pound of structure produces far greater benefit in an electric than in a gasoline-powered car because of the greater cost and weight of the power system. The best examples of lightweight vehicular structures are found in racing machines. Although racing cars are highly specialized, they embody techniques that may be useful in the design of lightweight electric vehicles (Costin and Phipps, 1962).

Fiberglass has proved to be a practical body material for limited-production cars. Since this material provides for a lighter weight shell than steel, it is probably a good choice for electric cars. (One likely candidate for a near-term electric car is the Meyers Manx, produced by B. F. Meyers and Company and sold in kit form only. This handsome car is essentially a fiberglass bathtub on a shortened Volkswagen chassis. The total weight, without prime mover, is less than 1,000 pounds.)

Particularly in urban use we have incentive for developing a regenerative braking system. There has been much talk about this possibility, but little activity of practical merit.

Vehicles for urban-suburban use have little need for aerodynamically clean design, since they are seldom driven at high speeds.

If we assume no further technical development of components, about the only things that can be done for an electric car designed for urban use are to choose efficient tires, to design for lightweight structure, and to design a regenerative braking system. Because of large heating-cooling loads imposed by accessories, it is reasonable to consider even insulated walls and double glass windows. Some efficiency in design over conventional practice may be gained by appropriately packaging the components in ways that are impossible with a gasoline engine.

These, then, are the general directions in which engineering attention can be expected to produce advances in electric vehicle design. Drawing our attention to just one of the potentially rewarding areas, let us consider the effect on cost of reducing the weight of a 3,000-pound electric car, of which 1,000 pounds is lead-acid battery, to 2,000 pounds. If an energy density of 15 watt-hours per pound is assumed, the battery will contain 15 kilowatt-hours. The cost of the battery will be about $300. (Price estimates for batteries vary considerably, but the U.S. Government procures lead-acid SLI batteries at prices of about $20 per kilowatt-hour (private communication from J. Reinman, U. S. Army Tank Center, Warren, Mich.). Reputable retail establishments sometimes sell batteries for $15 per kilowatt-hour, based on nameplate rating.) If the weight of the car is only 2,000 pounds, the energy requirement for the same range will drop by about one-fourth (see Table 8) for urban-suburban driving. The battery goes from 33 percent to 37 percent of vehicle weight, and propulsion power requirements decrease by approximately one-third; this means that if a 15-horsepower motor had been used for the 3,000-pound machine, a 10-horsepower motor would suffice for the 2,000-pound vehicle. At 20 pounds per horsepower and $15 per horsepower this represents a reduction of $75. The motor accounts for about 10 percent of the vehicle weight in either case.

Exclusive of the power plant, then, a 2,000-pound machine can cost as much as $150 more than a 3,000-pound machine before the heavier vehicle becomes more attractive in terms of first cost.

Table 8. EFFECT ON ENERGY REQUIREMENTS OF REDUCING VEHICLE WEIGHT FROM 3,000 TO 2,000 POUNDS

Driving mode	Energy requirements of 3,000-lb vehicle, kw-h/mile	Energy requirements of 2,000-lb vehicle, kw-h/mile	Change, %
Propulsion only			
Urban	0.189	0.135	—29
Suburban	0.193	0.130	—33
Turnpike	0.268	0.239	—11
Propulsion plus accessories			
Urban	0.322	0.268	—17
Suburban	0.260	0.197	—24
Turnpike	0.301	0.272	—10

Many similar comparisons could be made; the important point, however, is that the careful weighing of alternatives is a worthy prerequisite to actual design.

So far, the energy requirements of electric automobiles have been a principal subject. The whole of automotive mechanical design obviously involves much more. We are the beneficiaries of long years of significant progress in automotive technology. To appreciate our technological inheritance, we need list but a few of the dramatic early engineering accomplishments:

> The differential, which allowed the rear wheels to negotiate corners without scrubbing; the pneumatic tire, which made motoring less wearing for both vehicle and passenger; and steering mechanisms able to accommodate the different turning radii of front wheels.

Now that we are in a technically sophisticated and less romantic era of transportation technology than our forebears, it may be appropriate to view a vehicle as a box on four wheels. We need no longer view as a problem the development of, e.g., a satisfactory braking system. Today, by contrast, the "problems" affecting even mechanical design appear to spring from economic as much as from engineering considerations. For example, who would have foreseen, even 20 years ago, the impact of loan credit on the whole automotive industry, including the mechanical design of vehicles.

Technically, it appears that a completely satisfactory electric car can be built today. This is no news; it has been true for at least a decade. Even from a cost standpoint, satisfactory electric vehicles that are not prohibitively expensive can be built. From a solely economic viewpoint, however, the competition of the conventional car is overwhelming.

THE MODERN ELECTRIC CAR

The various prognosticators of electric automobile developments are correct in suggesting the small "runabout," particularly the commuter vehicle, as the first reincarnation of the electric car. Such a machine can most comfortably exploit the values placed on light weight, low speed, and small size. The technology is certainly at hand for the production of electric vehicles satisfactory for commuter service, mainly because great range is unnecessary.

More important, since the air pollution problem is most serious in the city core, attention should first be directed to urban-suburban commuters; they are, collectively, perhaps most responsible for and affected by airborne contaminants.

Although the air pollution problem provides the most recent mandate for an electric car, I believe that a number of automobile-associated urban problems could be alleviated by the electric automobile. Some of these crucial problems are air pollution, parking, and road space. Electric cars have the potential, through design, of providing relief in each of these problem areas. Electric vehicles, of themselves, can meet only the air pollution problem; however, more useful solutions may be found by a composite problem-solution approach than by attacks on individual problems.

Perhaps as great as the engineering problems associated with electric automobiles is the acceptance problem. Individuals have little natural incentive to possess electric vehicles, since gasoline-powered cars can, now and in the future, outperform electric cars on almost every score except that of holding down air pollution.

Even on this point, it is not clear that the electric power plant is the best of the alternative propulsion systems. Steam engines, turbines, and even improved spark-ignition engines have considerable potential for very low pollutant emission under the impress of an air pollution criterion. Nor are all electric systems necessarily free of emissions.

In addition, it is practically certain that electric cars will cost considerably more than equivalent gasoline-powered ones. People will not, then, gladly abandon their gasoline cars to buy electric cars. The incentives will have to be created. The banishment of gasoline-powered vehicles by legislation does not appear to me to be a practical possibility.

One incentive would strongly encourage the use of electric vehicles and, at the same time, take advantage of an inherent characteristic of the electric car. That incentive? A place to park. Public parking structures limited to electric vehicles would surely be incentive enough in most urban business districts. Such a scheme is favored, again, by the zero-emission characteristic of electric cars. Parking structures could be built underground or anywhere, with relatively little concern for ventilation. It seems reasonable to insist also that cars meet such requirements as maximum dimensions or certain construction features, so that they are compatible with the parking facilities.

Another proposal is to put commuter vehicles on rails. The steel wheel on the steel rail is, in a practical sense, unsurpassed for low rolling resistance. In many cities a number of railroad lines run from surrounding residential areas into the core areas. Perhaps arrangements could be made to use these tracks as rush-hour commuter lanes for electric vehicles capable of both on-track (steel wheel) and off-track (pneumatic tire) service. A speculative design of a vehicle for such dual service is shown in Figure 1.

There is room for a great deal of variety in design of electric cars; however, it may be in the public interest to place limits on the designs of electric commuter vehicles in consideration of the problems of air pollution, parking space, and road space and to establish special incentives for the use of these commuter vehicles.

TOWARD A TOTAL DESIGN

If one wishes to build an electric vehicle today, it can be done by assembling off-the-shelf components. Companies as well as individuals have done exactly that. Naturally — particularly in view of the markedly superior performance of gasoline-powered machines — it would be desirable to produce a better car than can be assembled from presently available components.

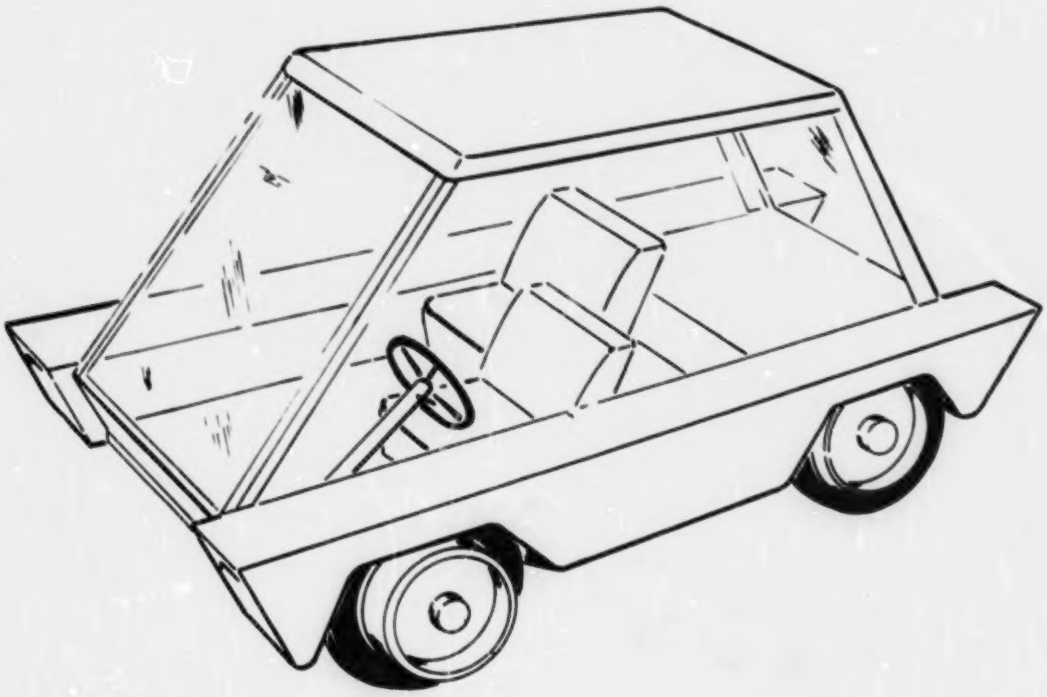

Figure 1. Two-passenger electric commuter vehicle for both road and rail service has rubber tires and steel wheels. The single traction motor is in the rear compartment; batteries are in the fenders. For entrance and exit, the windshield slides back into the roof.

We recognize that financial resources for progress toward the better electric vehicle will not be unlimited. It is therefore, worthwhile to inquire where research and development payoffs should be sought. Some possibilities are mentioned in the following paragraphs.

Most proponents of electric cars recognize the need for less-expensive, lighter weight batteries and motors. These technical areas probably call for some straightforward inventing — or at least for rediscovery of some dormant concepts.

The tires appear to have potential for considerable improvement in relation to the large amount of power they require on contemporary vehicles. Light weight is desirable, particularly in urban use. A good regenerative braking system would likewise improve propulsive efficiency for urban driving. For urban-suburban vehicles, we probably have little incentive for aerodynamically "clean" design.

The power requirement total for accessories, it was shown earlier, can be nearly as great as the requirement for propulsion. I believe we should expect commuters to demand the level of comfort afforded by year-round air conditioning. For the electric vehicle, this requirement will introduce a new direction for design, i.e., thermal design. Previously, we have been able to overpower the weather with heaters and air conditioners that have been merely added to the car. In electric automobiles, for climate control as well as for other accessory functions, the cost of providing extra power is incentive for the use of relatively efficient systems.

Electric cars may, at last, provide the long-lived automobile. Commercial vehicles often have service lives of 20 years. What if the life of private electric cars were 20 years rather than the 7 or 8 years now typical for automobiles? From the viewpoint of mechanical design, 20-year vehicle life is a practical possibility.

Although a number of engineering alternatives for electric vehicle design are well known and are found throughout the spectrum of modern technology, I conclude that electric cars are really favored only by entirely new designs — designs that are inherently suited to electric propulsion. In addition, we should view the electric car as an evolving vehicle. It has been proposed as a solution to air pollution problems, but we should not expect it to appear, miraculously, as a panacea.

Especially for the near future, the electric automobile holds somewhat limited promise. It will not be able to match, in either performance or range, the fire-breathing machines that are familiar to us. This is not to say that the promise it *does* hold is not worthy of aggressive pursuit — for if the electric car is viewed in the context of a responsibility toward improving our transportation systems rather than as merely another automotive alternative, we can hope to develop imaginative approaches that are genuine improvements over conventional schemes.

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ELECTROCHEMICAL SYSTEMS

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The search for more powerful and lighter weight electrochemical systems for electric vehicles can be facilitated by applying to the whole chemical gamut of the periodic chart certain basic principles of thermodynamics and kinetics. The fundamental thermodynamic relations governing an electrochemical cell or battery were first derived by Gibbs (1878) and may be expressed in the forms

$$E_w < E = -\Delta G/nF \tag{1}$$

$$dE/dT = \Delta S/nF \tag{2}$$

$$\Delta H = Q - W_e \tag{3a}$$

$$= \text{heat absorbed — electrical energy delivered} \tag{3b}$$

$$= TdW_e/dT - W_e \tag{3c}$$

$$= T\Delta S - (-\Delta G) \tag{3d}$$

$$= nFT(dE/dT) - nFE \tag{3e}$$

$$\text{Heat developed} = (-\Delta H - nFE_w \tag{4a}$$

$$= \text{enthalpy drop — Electrical energy delivered} \tag{4b}$$

where

E_w = working voltage under load

E = theoretical maximum reversible, or open circuit, voltage

T = temperature (Kelvin scale)

F = the Faraday, 96,487.3 ampere-seconds, or 26.802 ampere-hours

n = 1,2,3 . . . as the case may be

Q = heat absorbed by the battery

W_e = electrical energy delivered by the battery

H = enthalpy of the battery (its total energy plus the pressure-volume product)

S = entropy of the battery (measured by $\int dQ_{rev}/T$)

G = Gibbs function ("free enthalpy") of the battery (its enthalpy minus the temperature entropy product).

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The maximum voltage is given by the Gibbs function drop ("free enthalpy," "Gibbs free energy" drop) of the battery per unit charge delivered. The temperature coefficient of the maximum voltage is given by the entropy gain of the battery per unit charge delivered. The enthalpy gain of the battery is equal to the heat absorbed from the surroundings less the electrical energy delivered (nFE_w). Equations (3a) and (3b) express the first law of thermodynamics in its electrochemical form. Equations (3c), (3d), and (3e) are forms of the Gibbs-Helmholtz equation. The transition from (3a) to (3c) involves Carnot's theorem in the form $dW_e = QdT/T$ under reversible conditions. The heat developed by the battery is given by the enthalpy drop less the electrical energy delivered. Therefore, maximization of the electrical energy output (e.g., low internal resistance) has the beneficial effect of lowering the concurrent development of heat.

Thermodynamic information permits a calculation of the maximum or reversible voltage E of an electrochemical combination. For example, take the classic zinc-copper cell, a battery that was popular a century ago, before electricity became commercially available, when researchers had to assemble their own batteries out of inexpensive and readily available materials. The schematic diagram of the zinc-copper cell is

$$\begin{array}{llll} (-)Zn/Zn^{++}, SO_4^{=}, aq.// & SO_4^{=}, Cu^{++}, aq./Cu(+) & & \text{(A)} \\ V^\circ \quad -\ 0.7628 & +0.337 & \text{volts} & \\ (dV^\circ/dT)_{iso} \quad +\ 0.091 & +0.008 & \text{mv}/^\circ C & \end{array}$$

The standard electrode potential V°, and its isothermal temperature coefficient $(dV^\circ/dT)_{iso}$ (both referred to the standard hydrogen electrode SHE as zero at all temperatures) are taken from the compilation of de Bethune and Loud (1964). The Gibbs-Stockholm sign convention is followed, i.e., the electrode potential is positive if the electrode is the (+) terminal of a cell whose second electrode is the SHE. The familiar Latimer "oxidation potential" (Latimer, 1952) has the opposite sign and is not used here. The cell voltage E, following the Lewis-Stockholm sign convention (Christiansen and Pourbaix, 1954; Christiansen, 1960; Lewis and Randall, 1961; and Licht and de Bethune, 1957), is computed from

$$E(\text{Cell}) = V(\text{Right}) - V(\text{Left}) \qquad (5)$$

Note that the "Zellspannung" or "Cell Tension" recommended by C.I.T.C.E. is V(Left) – V(Right) (de Bethune, 1964), and is not used here.

For the zinc-copper cell (A), there results

$$E^\circ(25^\circ C) = (+0.337) - (-0.763) = +1.100 \text{ volts}$$

$$dE^\circ/dT = (+0.008) - (+0.091) = -0.083 \text{ mv}/^\circ C$$

$$E^\circ(100^\circ C) = +1.094 \text{ volts}$$

The cell reaction

$$Zn + Cu^{++} + SO_4^{=} = Cu + Zn^{++} + SO_4^{=} \qquad (B)$$

yields 2 faradays or 192,974.6 ampere-seconds of electricity at a maximum voltage of 1.100 volts. The maximum energy yielded as electrical work at 25°C is

$$\begin{aligned} 2.200 \text{ volt-faradays} &= 212{,}272 \text{ watt-seconds} \\ &= 58.964 \text{ watt-hours} \qquad (6) \end{aligned}$$

The volt-faraday is a convenient energy unit in electrochemical work. Its conversion factors are

$$\begin{aligned} 1 \text{ volt-faraday} &= 6.023 \times 10^{23} \text{ electron volts} && (7a) \\ &= 23.061 \text{ kilocalories} && (7b) \\ &= 91.51 \text{ Btu} && (7c) \\ &= 71{,}165 \text{ foot-pounds} && (7d) \\ &= 96{,}487.3 \text{ watt-seconds} && (7e) \\ &= 26.802 \text{ watt-hours} && (7f) \end{aligned}$$

At its 23-kilocalories equivalent, the volt-faraday represents, for example, 92 percent of the heat of combustion of a 25 (large) calorie "Metrecal" cookie.

In the zinc-copper cell, it takes a minimum of 112.50 grams of chemicals (if sulfate is used as the counter ion required by the law of electroneutrality) to yield 1 faraday of electricity. This comes out to 102.27 grams per volt-faraday. Division of this number into the conversion factor 26.802 watt-hours per volt-faraday yields the theoretical maximum energy density as 0.2621 kilowatt-hour per kilogram at 25°C. At 100°C, the corresponding figures would be 102.92 grams per volt-Faraday or 0.2604 kilowatt-hour per kilogram.

In Table 1, similar values are assembled for a number of well-known batteries. The numbers are based on the data of chemical thermodynamics (de Bethune and Loud, 1964; Latimer, 1952; Pourbaix, 1966; and Rossini et al., 1951) for the substances in their standard states and may differ from actual engineering performance data. For the lead storage battery, the theoretical maximum energy density is about 0.17 kilowatt-hour per kilogram. For the zinc-silver, zinc-copper, and cadmium-nickel batteries, it is about 50 percent higher. For the hydrogen-oxygen fuel cell, the theoretical maximum energy density jumps spectacularly to 3.5 kilowatt-hours per kilogram, i.e., to 20-fold that of the lead storage cell. This figure gives the order of magnitude of the optimum that can be reached in energy densities by going to light-weight active materials.

Table 1. STANDARD VOLTAGES AND MAXIMUM ENERGY DENSITIES FOR A NUMBER OF COMMON BATTERIES[a]

E°, volts at 25°C	E°, volts at 100°C	Weight/charge, g/F	Maximum energy density, kw-h/kg at 25°C	Maximum energy density, kw-h/kg at 100°C
(—)Pb/PbSO$_4$, H$_2$SO$_4$, PbSO$_4$/PbO$_2$(+)				
2.0408	2.1528	321.296	0.1702	0.1796
(—)Zn/ZnSO$_4$,aq.//CuSO$_4$,aq./Cu(+)				
1.100	1.094	112.50	0.2651	0.2604
(—)Zn/Zn(OH)$_2$,KOH,Ag$_2$O/Ag(+)				
1.590	1.563	157.578	0.2704	0.2658
(—)Cd/Cd(OH)$_2$,KOH, Ni(OH)$_2$/NiO$_2$(+)				
1.299	1.284	119.566	0.2912	0.2878
(—)H$_2$/H+,H$_2$O/O$_2$(+)				
1.229	1.167	9.008	3.656	3.472

[a] Based on standard data of chemical thermodynamics (de Bethune and Loud, 1964; Latimer, 1952; National Bureau of Standards, 1952).

Theoretical maximum energy densities may be expected to exceed operational energy densities by a factor ranging from 3:1 to 10:1 or greater. The theoretical maximum energy density does not take into account three operational factors that drastically cut down the ratio of energy to weight: (1) voltage losses due to polarization and/or internal resistance, (2) the necessary weight of electrolyte, separator, box, and connectors, (3) the limited depth of discharge (50 to 75%) per cycle permissible if cycle life is not to be sacrificed.

In the lead storage cell, for example, a good quality 12-volt automobile battery, sold by Sears-Roebuck, is rated at 70 ampere-hours (20 hours rate) and weighs 46 pounds (21 kilograms). On slow discharge, this battery yields 840 watt-hours, or 18.2 watt-hours per pound, which is 40.2 watt-hours per kilogram, or 1:4.2 of the theoretical maximum energy density of 0.17 kilowatt-hour per kilogram. On fast discharges, of the type needed in automobile propulsion, this battery might yield only 8 to 12 watt-hours per pound, or 18 to 26 watt-hours per kilogram, i.e., between 1:10 and 1:6.5 of the theoretical maximum.

Dalin, in another part of this book, quotes the following operational energy densities, in watt-hours per pound. They are here converted to watt-hours per kilogram and compared with theoretical figures from Table 1.

	Operational w-hr/lb	Operational w-hr/kg	Theor. w-hr/kg	Ratio Oper:theor
Zinc-silver	40 to 50	88 to 110	270	1:3 to 1:2.5
Cadmium-nickel	18 to 20	40 to 44	290	1:7

The present theoretical study of novel anode and cathode materials is based extensively on the de Bethune-Loud (1964) compilation of electrode potentials and isothermal temperature coefficients. These are all referred to the SHE as zero. However, the standard hydrogen electrode is an *inconvenient* reference point for the study of cathodes and anodes of potential usefulness to electric vehicles. Therefore, *other reference electrodes have been chosen as a basis for comparison. They include two reference anodes: lithium and zinc-zinc hydroxide, and two reference cathodes: fluorine and sulfur.* These reference electrodes are much closer to the types of half-cells being developed in actual engineering studies. Two of them, the lithium anode and the fluorine cathode, represent the extremes attainable in electrode potential and lightness of weight. The characteristics of these four reference electrodes are given in Table 2.

Table 2. CHARACTERISTICS OF THE FOUR REFERENCE ELECTRODES USED IN THIS STUDY[a]

(referred to the SHE as zero at all temperatures)

Reference anodes	
Li/Li^+	$Zn/Zn(OH)_2,OH^-$
$V^\circ = -3.045$ v	$V^\circ = -1.245$ v
$(dV^\circ/dT)_{iso} = -0.534$mv/°C	$(dV^\circ/dT)_{iso} = -1.002$ mv/°C
6.94 g/F	$(d^2V^\circ/dT^2)_{iso} = -5.978\ \mu v/(°C)^2$
	49.698 g/F
Reference cathodes	
F^-/F_2	$S^=/S$
$V^\circ = +2.87$ v	$V^\circ = -0.447$ v
$(dV^\circ/dT)_{iso} = -1.83$ mv/°C	$(dV^\circ/dT)_{iso} = -0.93$ mv/°C
19.00 g/F	16.033 g/F

[a] Data from de Bethune and Loud, 1964.

In Table 3, chemical thermodynamic data have been assembled for 28 possible anodes of 15 chemical elements. In the table, the anodes are listed in *alphabetical order of chemical symbols of the major element*. In the periodic chart, the elements considered are arrayed in the groupings

Anode elements

H																	*
Li	Be											*	*	N	*	*	*
Na	Mg											Al	*	*	*	*	*
K	Ca	Sc	*	*	*	*	Fe	*	*	*	Zn	*	*	*	*	*	*
*	*	Y	*	*	*	*	*	*	*	*	Cd	*	*	*	*	*	*
*	*	(15 *)	*	*	*	*	*	*	*	*	*	*	Pb	*	*	*	*

For each anode, the tables lists the following information:

The weight-to-charge ratio (grams per faraday) of the electrode reaction, including the weight of any necessary counter ions indicated as (Li^+) or (H^+).

The electrode potential V° at 25°C, and the isothermal temperature coefficient $(dV^\circ/dT)_{iso}$ at 25°C, both referred to SHE as zero at all temperatures.

The anode potential E° versus the fluorine cathode and/or the sulfur cathode, calculated at 25° and 100°C. The anode potentials are all given the negative sign, to correspond to their observed (—) polarity in the cells; the cell voltages are given by the same number without the negative sign.

The maximum energy density, in kilowatt-hours per kilogram, for the given anode when coupled with the fluorine cathode and/or the sulfur cathode, at 25° and 100°C.

The optimum thermodynamic performance is that of the lithium-fluorine cell with a maximum voltage of 5.9 volts and an energy density of 6.1 kilowatt-hours per kilogram. The aluminum hydroxide, aluminum sulfide, calcium, magnesium, sodium, potassium, yttrium, hydride, and hydrazoic acid anodes are close seconds, when coupled with a fluorine cathode, with voltages ranging between 5.1 and 6.2 volts and energy densities between 5.1 and 2.7 kilowatt-hours per kilogram. The beryllium, acid hydrogen, alkaline hydrogen, hydrazine, and scandium anodes give voltages between 2.9 and 4.9 volts, *versus* fluorine, and energy densities between 2.2 and 5.4 kilowatt-hours per kilogram. The aluminum fluoride, cadmium, iron, ammonium hydroxide, and zinc anodes give voltages between 3.3 and 4.9 volts, *versus* fluorine, and energy densities between 1.2 and 1.9 kilowatt-hours per kilogram.

Table 3. CHARACTERISTICS OF ANODES*

($V°$ and $(dV°/dT)_{iso}$ referred to SHE as zero at all temperatures)

(−) Anodes, g/F $V°(25°)$, v $(dV°/dT)_{iso}$, mv/°C	versus $F^-/F_2(+)$ E°(v) and kw-h/kg at 25°C E°(v) and kw-h/kg at 100°C		versus $S^=/S(+)$ E°(v) and kw-h/kg at 25°C E°(v) and kw-h/kg at 100°C	
Al/Al^{+++}; 899				
−1.662	−4.532	4.337	—	—
+0.504	−4.357	4.174	—	—
$Al/Al(OH)_3,OH^-(Li^+)$; 32.938				
−2.30	−5.17	2.668	−1.853	1.0142
−0.93	−5.10	2.632	−1.853	1.0142
$AlF_6^{-3},F^-(Li^+)$; 60.873				
−2.069	−4.939	1.657	−1.622	0.5653
−0.20	−4.816	1.616	−1.577	0.5496
Al/Al_2S_3, $S^=(Li^+)$; 31.966				
−2.595	−5.465	2.874	−2.148	1.1966
−1.66	−5.452	2.867	−2.203	1.2273
Be/Be^{++}; 451				
−1.847	−4.72	5.38	—	—
+0.565	−4.54	5.17	—	—
Ca/Ca^{++}; 20.04				
−2.866	−5.736	3.938	−2.419	1.797
−0.175	−5.612	3.853	−2.363	1.756
$Ca/Ca(OH)_2,OH^-(Li^+)$; 43.99				
−3.02	—	—	−2.57	1.148
−0.965	—	—	−2.57	1.148
Cd/Cd^{++}; 56.20				
−0.4029	−3.27	1.243	—	—
−0.093	−3.14	1.194	—	—
$Cd/Cd(OH)_2$, $OH^-(Li^+)$; 80.153				
−0.809	−3.68	0.9947	−0.362	0.1009
−1.014	−3.62	0.9785	−0.368	0.1025
Fe/Fe^{++}; 27.93				
−0.4402	−3.31	1.890	—	—
+0.052	−3.17	1.810	—	—

Table 3. (continued)

(−) Anodes, g/F $V°(25°)$,v $(dV°/dT)_{ave}$, mv/°C	versus $F^-/F_2(+)$ E°(v) and kw-h/kg at 25°C E°(v) and kw-h/kg at 100°C		versus $S^-/S(+)$ E°(v) and kw-h/kg at 25°C E°(v) and kw-h/kg at 100°C	
$Fe/Fe(OH)_2$, $OH^-(Li^+)$; 51.873				
−0.877	−3.75	1.418	−0.430	0.1697
−1.06	−3.69	1.395	−0.440	0.1737
H_2/H^+, H_2O; 1.008				
0.0000	−2.87	3.845	—	—
0.000	−2.73	3.657	—	—
$H_2/H_2O,OH^-(Li^+)$; 24.956				
−0.82806	−3.698	2.255–	−0.381	0.2491
−0.8342	−3.623	2.209	−0.373	0.2439
$H_2/H^-(Li^+)$; 7.948				
−2.25	−5.12	5.092	—	—
−1.57	−5.10	5.072	—	—
K/K^+; 39.100				
−2.925	−5.795	2.673	−2.478	1.205
−1.080	−5.739	2.647	−2.591	1.260
Li/Li^+; 6.94				
−3.045	−5.915	6.111	−2.598	3.031
−0.534	−5.818	6.011	−2.566	2.996
Mg/Mg^{++}; 12.16				
−2.363	−5.23	4.50	−1.916	1.821
+0.103	−5.09	4.38	−1.839	1.748
$Mg/Mg(OH)_2,OH^-(Li^+)$; 36.11				
−2.69	—	—	−2.24	1.151
−0.945	—	—	−2.24	1.151
Na/Na^+; 22.997				
−2.714	−5.584	3.563	−2.267	1.557
−0.772	−5.505	3.513	−2.255	1.548
$NH_4OH/N_2,OH^-(Li^+)$; 36.630				
−0.736	−3.61	1.74	−0.289	0.147
—	—	—	—	—
$N_2H_5^+/N_2,H^+(F^-)$; 13.0135				
−0.23	−3.10	2.595	—	—
−0.84	−3.03	2.537	—	—

Table 3. (continued)

(—) Anodes, g/F $V°(25°)$,v $(dV°/dT)_{iso}$,mv/°C	versus $F^-/F_2(+)$ E°(v) and kw-h/kg at 25°C E°(v) and kw-h/kg at 100°C		versus $S^=/S(+)$ E°(v) and kw-h/kg at 25°C E°(v) and kw-h/kg at 100°C	
$HN_3(g)/N_2,H^+$; 43.032				
—3.40	—6.27	2.71	—	—
—1.193	—6.22	2.69	—	—
$Pb/PbSO_4,SO_4^=(H^+)$; 152.646				
—0.3588	—3.23	0.5671	—	—
—1.015	—3.17	0.5566	—	—
Sc/Sc^{+++}; 14.97				
—2.077	—4.947	3.903	—	—
+0.25	—4.791	3.780	—	—
Y/Y^{+++}; 29.64				
—2.372	—5.242	2.888	—	—
+0.18	—5.091	2.805	—	—
Zn/Zn^{++}; 32.69				
—0.7628	—3.63	1.882	—	—
+0.091	—3.49	1.810	—	—
$Zn/Zn(OH)_2,OH^-(Li^+)$; 56.638				
—1.245	—4.115	1.458	—0.798	0.2943
—1.002	—4.053	1.436	—0.803	0.2962
$Zn/ZnS,S^=(Li^+)$; 55.663				
—1.405	—	—	—0.958	0.4613
—0.85	—	—	—0.952	0.4584

[a] Data from de Bethune and Loud, 1964.

Table 4 gives similar information for 21 possible cathodes of 13 chemical elements, listed in *alphabetical order of chemical symbols of the major element*. In the periodic chart, the elements considered are arrayed in the groupings

Cathode elements

•																	•
•	•											•	•	N	O	F	•
•	•											•	•	•	S	Cl	•
•	•	•	•	•	Cr	Mn	Fe	•	Ni	•	•	•	•	•	•	Br	•
•	•	•	•	•	•	•	•	•	•	Ag	•	•	•	•	•	•	Xe
•	•	(15 •)	•	•	•	•	•	•	•	•	•	•	Pb	•	•	•	•

Table 4. CHARACTERISTICS OF CATHODES[a]

($V°$ and $(dV°/dT)_{iso}$ referred to SHE as zero at all temperatures)

Cathodes (+), g/F	versus (—)Li/Li^+		versus (—)$Zn/Zn(OH)_2$	
$V°(25°)$,v	E°(v) and kw-h/kg at 25°C		E°(v) and kw-h/kg at 25°C	
$(dV°/dT)_{iso}$,mv/°C	E°(v) and kw-h/kg at 100°C		E°(v) and kw-h/kg at 100°C	
$OH^-,Ag_2O/Ag$; 124.881				
+0.345	+3.390	0.6839	+1.590	0.2704
—1.337	+3.330	0.6771	+1.563	0.2658
$OH^-,Ag_2O_3/Ag$; 52.97				
+0.564	+3.609	1.615	+1.809	0.4723
—	—	—	—	—
Br^-/Br_2; 79.916				
+1.0652	+4.110	1.268	+1.310	0.2709
—0.629	+4.103	1.266	+1.338	0.2767
$OH^-,Br^-/BrO_3^-$; 30.327				
+0.61	+3.655	2.628	+1.855	0.6213
—1.287	+3.599	2.588	+1.834	0.6142
Cl^-/Cl_2; 35.457				
+1.3595	+4.404	2.784	+2.604	0.7580
—1.260	+4.350	2.750	+2.585	0.7523
$Cr^{+++}/Cr_2O_7^{=}$; 29.69				
+1.33	+4.375	3.201	—	—
—1.263	+4.320	3.161	—	—
$Cr(OH)_3/CrO_4^{=}$; 62.69				
—0.13	+2.915	1.122	+1.115	0.2659
—1.675	+2.837	1.092	+1.065	0.2540
F^-/F_2; 19.00				
+2.87	+5.915	6.111	+4.115	1.713
—1.83	+5.818	6.011	+4.053	1.687
F^-/F_2O; 14.004				
+2.15	+5.195	6.648	—	—
—1.184	+5.146	6.585	—	—
$(Li^+)OH^-,Fe(OH)_3/FeO_4^{=}$; 66.285				
+0.72	+3.765	1.378	+1.965	0.4284
—1.62	+3.684	1.348	+1.918	0.4182

Table 4. (continued)

Cathodes (+), g/F V°(25°),v $(dV°/dT)_{iso}$,mv/°C	versus (—)Li/Li$^+$ E°(v) and kw-h/kg at 25°C E°(v) and kw-h/kg at 100°C		versus (—)Zn/Zn(OH)$_2$ E°(v) and kw-h/kg at 25°C E°(v) and kw-h/kg at 100°C	
Mn^{++}/MnO_4^-; 32.341				
+1.51	+4.555	3.775	—	—
−0.66	+4.545	3.767	—	—
$OH^-,MnO_2/MnO_4^-$; 51.654				
+0.588	+3.633	1.662	+1.833	0.4847
−1.778	+3.540	1.619	+1.775	0.4694
NH_4^+, N_2/HN_3; 23.028				
+1.96	+5.005	4.476	—	—
−0.14	+5.035	4.503	—	—
(F^-), H^+, $N_2/H_2N_2O_2$; 51.023				
+2.65	+5.695	2.633	—	—
−0.09	+5.662	2.618	—	—
OH^-, $Ni(OH)_2/NiO_2$; 63.371				
+0.490	+3.535	1.348	+1.735	0.4113
−1.19(?)	+3.485	1.328	+1.721	0.4079
H^+, H_2O/O_2; 9.008				
+1.229	+4.274	6.379	—	—
−0.846	+4.251	6.345	—	—
OH^-, H_2O/O_2; 17.008				
+0.401	+3.446	3.857	+1.646	0.7058
−1.680	+3.360	3.760	+1.595	0.6839
$SO_4^=$, $PbSO_4/PbO_2$; 169.666				
+1.682	+4.727	0.7174	—	—
+0.326	+4.792	0.7272	—	—
$S^=/S$; 16.033				
−0.447	+2.598	3.031	+0.798	0.3254
−0.93	+2.568	2.996	+0.803	0.3274
$SO_4^=/S_2O_8^=$; 48.033				
+2.01	+5.055	2.188	+3.265	0.8954
−1.26	+4.999	2.164	+3.245	0.8899
$H^+,H_2O,Xe/XeO_3$; 30.891				
+1.8	+4.8	3.4	—	—
—	—	—	—	—

[a] Data from de Bethune and Loud, 1964.

In Table 4, the weight-to-charge ratio in grams per faraday *generally does not include* the weight of any counter ions required by the law of electroneutrality. The maximum energy density in kilowatt-hours per kilogram then represents a ceiling that one would not expect to attain even under the most idealized conditions. For example, the maximum energy density of the fluorine cathode is listed in Table 4 at 1.713 kilowatt-hours per kilogram *versus* the $Zn/Zn(OH)_2$ anode at 25°C. The inclusion of one mole of lithium ion Li^+ as a necessary counter ion would drop this maximum figure to 1.458 kilowatt-hours per kilogram, before any further losses are taken into account. Similarly, the maximum energy density of the sulfur cathode, listed as 0.3254 kilowatt-hour per kilogram *versus* the $Zn/Zn(OH)_2$ anode, is dropped to a maximum of 0.2934 kilowatt-hour per kilogram by inclusion of one mole of Li^+ as a counter ion. Where the counter ion is explicitly mentioned, as (Li^+) or (F^-), its weight is included in the calculations.

The cathode potentials E° are given *versus* the lithium anode and/or zinc-zinc hydroxide anode, calculated at 25° and 100°C. They are listed with the positive sign, to correspond to their observed (+) polarity in the cells. These potentials equal, as given, the standard voltages of the cells: (—)anode/cathode(+).

The optimum thermodynamic performance is that of the fluorine, oxygen fluoride, and acid oxygen cathodes when coupled with a lithium anode, with maximum energy densities of over 6 kilowatt-hours per kilogram. Other cathodes whose maximum energy densities exceed 2 kilowatt-hours per kilogram, when coupled with lithium, include the bromate-bromide, chlorine, acid dichromate, acid permanganate, hydrazoic acid, hyponitrous acid, alkaline oxygen, sulfur, peroxydisulfate, and xenic acid cathodes. Cathodes of silver-III oxide, bromine, alkaline chromate, alkaline ferrate, alkaline permanganate, and nickel-IV oxide give energy densities between 1 and 2 kilowatt-hours per kilogram when coupled with a lithium anode.

Under actual conditions, the reversible, or open circuit, voltage E would differ from the standard voltage E° by a small term, usually of the order of ± 100 to 200 millivolts, calculable from the Nernst Equation, which has also been called the Electrochemical Law of Mass Action. As applied to a single electrode potential, where the electrode reaction can be written in the generalized form:

$$Ox + ne^- = Red \tag{8a}$$

(written in either direction)

the Nernst equation (with the Gibbs-Stockholm sign convention) takes the form

$$V = V^\circ + (RT/nF)\ \ln\ (Ox)/(Red) \tag{8b}$$

$$= V^\circ + (0.05916\ \text{volt}/n)\ \log\ (Ox)/Red\ \text{at}\ 25^\circ C \tag{8c}$$

where (Ox) and (Red) denote the activities, or activity products, of the electromotively active chemical substances, in their oxidized and reduced forms, that appear in the electrochemically balanced expression for the half-cell reaction.

KINETIC FACTORS — INTERNAL AND POLARIZATION RESISTANCES

The kinetics of the electrode reactions become of paramount importance in dealing with an operating battery. The inequality contained in equation (1) was originally formulated by Gibbs (1878) in the form

$$(V''-V') \leqq -d\zeta/de \tag{9}$$

where V′ and V″ are, in Gibbs' words, "the electrical potentials in pieces of the same kind of metal connected with the anode and cathode, respectively," and $d\zeta$ and de become ΔG and nF in modern notation. Gibbs' inequality (equation 9) is more useful than its modern counterpart (equation 1) since it applies equally to the discharge cycle ($V''>V'$) and to the charge cycle ($V'>V''$). It is well known that the anode on discharge becomes the cathode on recharge, and *vice-versa*.

The inequality in equations (1) and (9) can also be expressed, for a discharging battery, by

$$V'' - V' = E_w = iR_x = E - iR_i \tag{10}$$

where

i = total current in amperes

R_x = external or load resistance

R_i = internal resistance, including electrode polarization "resistances," if any.

The maximum current yielded by a cell is its short-circuit current ($R_x=0$) equal to E/R_i. The power output is zero at short circuit.

A battery yields its maximum power, equal to $E^2/4R_i$, at a current output equal to one-half the short-circuit current. In general, the power output is given by the parabolic function

$$P = E_w i = Ei - i^2R_i \tag{11}$$

This result shows the manifest importance of minimizing R_i to obtain an operational battery.

The internal resistance can be broken up into the ohmic resistance R_a of the electrolyte, equal to $\rho L/A$, where

ρ = resistivity

L = electrode spacing,

A = projected (geometrical) electrode area, plus the polarization "resistances" R_A and R_C of anode and cathode. The polarization resistances are not constants; they vary with the current density I. For activation polarization (overvoltage), the resistance has the limiting value

$$R_{Act}(\text{ohms}) = b/2 \cdot 2.303\ I_oA \qquad (12a)$$

at zero current density and decreases with increasing current according to

$$R_{Act}(\text{ohms}) = (b/IA)\ \log I/I_o \qquad (12b)$$

where b and I_o are the Tafel parameters of the activation overpotential (Vetter, 1961). For concentration or transport polarization, the resistance has the limiting value

$$R_{conc}(\text{ohms}) = RT/nFI_dA \qquad (13a)$$

at zero current density and increases with increasing current according to

$$R_{conc}(\text{ohms}) = (RT/nFIA)\ \ln I_d/(I_d\text{-}I) \qquad (13b)$$

going to infinity as I approaches the limiting diffusion (transport) current I_d.

In an operational battery, the electrolyte resistivity should not exceed 10 ohm-centimeters (e.g., the resistivity of a 1 molar sodium chloride brine). Consider an electrode spacing of 1 millimeter (0.03937 inch). The unit area resistance $A \cdot R_s$ is then equal to

1 ohm-cm^2 (or 0.00108 ohm-ft^2)

This value probably represents a reasonable norm, and at the same time, an operational upper limit, for the internal resistance of a battery. At an A·R value of 1 ohm-square centimeter, an output current of 600 milliamperes per square centimeter (557 amperes per square foot) means a voltage loss of 600 millivolts, e.g., about half of the open-circuit voltage of the hydrogen-oxygen fuel cell.

To the electrolyte resistance must be added the polarization "resistances" arising from the kinetics of the electrode reactions, as given by equations (12) and (13). *Since activation and transport polarizations act in series,* and since R_{Act} decreases while R_{conc} increases with increasing current, *their combined effects can often be approximated by a linear polarization* up to about 99 percent of the limiting transport current (de Bethune, 1960). Numerical calculations, based on equations (12) and (13), lead to Table 5, in which are given the *combined activation and polarization unit area resistances* of electrodes having the following kinetic parameters.

Tafel constants: $b = 0.120$ volt

$I_o = 10, 1, 0.1,$ and 0.01 a/cm^2

Transport constants: $n = 1$, $I_d = 10, 1$ a/cm^2

Table 5. COMBINED ACTIVATION AND CONCENTRATION (TRANSPORT) POLARIZATION RESISTANCES OF ELECTRODES AS A FUNCTION OF CURRENT DENSITY[a]

Tafel constants: b=0.120 volt, I_o=10, 1, 0.1, and 0.01 a/cm²
Transport constants: n=1, I_d = 10, 1 a/cm²

	I_d=10 a/cm² I_o=10 a/cm²	I_d=10 a/cm² I_o=1 a/cm²	I_d=10 a/cm² I_o=0.1 a/cm²	I_d=10 a/cm² I_o=0.01 a/cm²
Current density	A•R	A•R	A•R	A•R
(a/cm²)	(ohm-cm²)	(ohm-cm²)	(ohm-cm²)	(ohm-cm²)
0	0.0052	0.028	0.26	2.6
0.1	0.0052	0.028	0.25	1.2
0.2	0.0052	0.028	0.18	0.78
0.5	0.0052	0.028	0.17	0.41
0.8	0.0052	0.028	0.14	0.29
0.9	0.0052	0.028	0.13	0.26
0.99	0.0052	0.028	0.12	0.24
1.00	0.0052	0.028	0.12	0.24

	I_d=1 a/cm² I_o=10 a/cm²	I_d=1 a/cm² I_o=1 a/cm²	I_d=1 a/cm² I_o=0.1 a/cm²	I_d=1 a/cm² I_o=0.01 a/cm²
Current density	A•R	A•R	A•R	A•R
(a/cm²)	(ohm-cm²)	(ohm-cm²)	(ohm-cm²)	(ohm-cm²)
0	0.028	0.052	0.28	2.6
0.1	0.030	0.053	0.28	1.2
0.2	0.033	0.055	0.26	0.81
0.5	0.040	0.063	0.21	0.45
0.8	0.045	0.078	0.18	0.33
0.9	0.069	0.092	0.19	0.33
0.99	0.123	0.146	0.24	0.36
1.00	∞	∞	∞	∞

[a] The body of the Table gives the unit area resistance A•R of the electrode in ohm-cm² (1 ohm-cm² = 0.155 ohm-in.² = 0.001076 ohm-ft²).

The degree of constancy of the A·R values in Table 5 measures the reliability of the approximation of linear polarization as a substitute for the combined nonlinear activation and transport polarizations. For the kinetic parameters chosen, the polarization resistance of the electrode is almost everywhere a small fraction of 1 ohm-square centimeter (up to 99% of the limiting transport current). Beyond 99 percent of the limiting current, the polarization voltage goes rapidly to infinity, and the current output remains at its transport limited value.

Kinetic parameters I_0 and I_d significantly lower than those considered in Table 5 would tend to make the battery non-operational. For example, I_0 and I_d values of 10^{-4} amperes per square centimeter each would correspond to a combined unit area resistance of approximately 1,000 ohm-square centimeter up to 99 percent of I_d.

CORROSION — CELL UNIFORMITY

Batteries made up of active, free energy rich chemicals can be expected to suffer from corrosion problems in which these active chemicals react through other reaction paths than those anticipated or desired. This can be illustrated by the role of the cathodic oxygen reaction

$$O_2 + 4H^+ + 4e^- = 2H_2O \tag{14}$$

in corrosion and in a fuel cell. For corrosion control, reaction (14) must be inhibited, e.g., by paint films or chemical inhibitors, or it must be satisfied by a superimposed cathodic protection current to supply the needed electrons from another source than the metal under attack. In a fuel cell, reaction (14) needs to be actively promoted on the fuel cell's catalytic cathodic surfaces. It must also be vigorously controlled and inhibited elsewhere in the fuel cell to prevent destructive corrosion of the cell.

Cell uniformity, not only mechanical and geometrical, but also chemical, electrochemical, and thermal uniformity, becomes of paramount importance when cells are stacked together in series to form a battery (e.g., the voltaic pile). Experience has shown that the weakest cell in a pile can actually reverse its voltage by polarization when it is driven by the other cells of the pile generating a current in excess of its own intrinsic short-circuit current. In such a situation, the weak cell is rapidly destroyed by the continued operation of the pile and greatly reduces the effectiveness of the whole battery. *Stringent control of cell uniformity* becomes of paramount importance in ensuring good battery operating characateristics and good cycle life. A battery, like a chain, is no better than its weakest cell.

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SEPARATOR SYSTEMS

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INTRODUCTION

The science and technology of synthetic membrane systems has been developed, particularly in the past decade, to the point where new materials with a wide variety of useful properties are available for use as battery separators. Some of these new materials are beginning to find their way into battery separators, and with the current development of new battery systems, particularly those of the type required for the electric vehicle, many new developments may ensue.

For many of the new battery systems now under development, the availability of new separator systems is an absolute requirement. Even in older systems such as the lead-acid batteries, the availability of new separator materials has led to improved performance and reliability. The failure of a large fraction of all batteries may be traced to the inadequacy or malfunction of the separator.

In this contribution I will describe the recent advances in the physics, chemistry, and technology of battery systems that may be applied to advantage in the fabrication of new and superior battery separators. I will not describe all of the different materials and systems that may be employed, but rather will indicate some of each class.*

Different battery systems require rather different kinds of separator systems. The separator must, of course, allow for the passage of the ions that carry the current and, in some cases, they also must permit the ready flow of solvent. In other systems, it is desirable to inhibit or even prevent solvent flow. In some systems certain ionic or molecular species should be prevented from moving across the separator to the opposite electrode. In most batteries the separators must prevent the movement of particulate matter away from the plates and retard, if not inhibit, dendritic growth, particularly from one plate toward the other.

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* Dr. Gregor's presentation gives an extensive background of material from the literature; these references are cited directly as he provided them. Since he describes various materials and systems as examples of their class, Dr. Gregor does not regard the literature citations as an exhaustive bibliography on separator systems.

CLASSIFICATION OF SEPARATORS

Separator systems are best classified on the basis of pore diameters and the nature of those chemical groups fixed to the pore walls. Although we tend to think of films having cylindrical pores extending through the membrane, each at right angles to each face, real systems are not at all like this with the possible exception of some new films wherein holes are "punched through" the membrane by radiation*(1)*. Separators usually have pores of varying diameter that extend in a highly branched configuration in all directions from one membrane face to the other. Indeed, with many membranes one should think more of a three-dimensional polymeric gel-like structure; certain membranes are best viewed simply as solid solutions, with no pores, as such. Table 1 lists pore diameters expressed both in microns (μ) and Angstrom (A) units; the range of pore diameters extends over six orders of magnitude for membranes now available.

Table 1. PORE AND SOLUTE DIAMETERS

	Microns (μ)	Angstroms (A)	
	100		
	1 mil →		
Millipore	10		
	1	10,000 A	
	0.1	1,000	Colloids
		100	
		10	Proteins
		1	Na+, Cl−

The selective transport of an ionic and/or molecular specie across a membrane is controllable by relatively few parameters: size; charge (whether negative or positive); chemical reactivity with a fixed (charge) group; solubility.

MACROPOROUS MEMBRANES ($d > 1\mu$)

Highly porous membranes, having pore diameters from 1 to 10 microns, are conveniently prepared by mixing a molten polymer with fine particles of uniform diameter, the particulate matter occupying approximately three-fourths the volume of the suspension. One then extrudes a sheet from this suspension and, after the polymer has solidified, dissolves the particulate matter, leaving the porous matrix. Finely divided salt particles have been used for this surface, as have starch granules, the latter because of their rather uniform size. Such films are available commercially from several sources, including the Electric Storage Battery Company*(2)*. The polymers used for this purpose include polyethylene, polyvinylchloride, and certain of the fluoro-polymers. A somewhat analogous procedure starts with solid particles of the polymer, which are sintered together either by heat or by the use of an appropriate solvent to cement the particles*(3)*. The lower limit of the pore diameters for these films is about 1 micron, because this is approximately the size of the smallest particles available for providing the voids or for cementation.

MICROPOROUS (1 μ >d>100A) AND MOLECULAR PORE (100A >d>1A) MEMBRANES

Polymeric membranes of graded porosity are usually prepared by dissolving the polymer in one solvent, casting a film and allowing the solvent to evaporate partially, then coagulating the film by immersion in a non-solvent. Other kinds of polymeric films, particularly the familiar cellophane film, are produced by extruding a solution of a cellulosic derivitive (viscose) into a bath that partially coagulates the film and simultaneously converts it back to the original cellulose*(4)*.

Control of the porosity of films of this type has been the subject of many investigations; the general principles and procedures described by Elford are still commonly employed*(5, 6)*. The higher the solvent content of the film at the time of coagulation, the greater its porosity, as a general rule. Elford described films that were remarkably homoporous, prepared by the use of mixed solvents both for dissolution of the polymer and for coagulation. These general procedures apparently have been followed in the preparation of Millipore membranes, which are usually composed of mixed derivatives of cellulose; similar membranes have been prepared from mixtures of cellulose acetate and cellulose nitrate, as an example. Table 1 lists the stated pore diameters of Millipore membranes.

Control of porosity of nitrocellulose membranes has been described by Sollner and Gregor, among others, who showed that by drying a coagulated nitrocellulose film in atmospheres of progressively lowered relative humidity one obtains membranes of graded porosity*(7, 8)*. This principle has been extended by Carr*(9)*, who re-swelled nitrocellulose membranes in mixtures of swelling solvents, in this case alcohol-water mixtures, then coagulated the film in water and obtained films that showed a remarkable degree of discrimination between molecules of low molecular weight, with estimated pore diameters varying from about 5 to 50 Angstrom units.

Similarly, Craig*(10)* has varied the porosity of cellulosic membranes by using swelling solvents and by stretching membranes uniaxially to convert the pores from a spherical to an elliptical shape.

With certain kinds of coagulated, porous membranes, drying of the film may reduce its porosity. This can be avoided by use of a mixture of two polymers, one being strongly hydrophilic and the other being an insoluble, hydrophobic matrix material. Porosity can be maintained in a swelling solvent with such films. An example of membranes of this kind has been described by Mindick*(11)*, who cast interpolymer membranes from a mixture of a copolymer of vinylchloride and acrylonitrile (Dynel, Union Carbide Company) and polyvinylpyrrolidone (PVP), both dissolved in an appropriate common solvent. After casting the film and allowing the solvent to evaporate, one obtains a continuous phase of the water-insoluble polymer (Dynel) and the macroscopic pores contain the hydrophilic polymer (PVP). This general interpolymer technique, first described by Gregor*(12)*, is useful because it is very flexible, it allows one to use many different polymer mixtures (although selecting an appropriate solvent may be rather difficult), and it permits one to produce films with high-speed equipment at relatively low cost. Additional stability can be obtained by the use of appropriate cross-linking agents, although their use makes the formulation somewhat more complex.

DETERMINATION OF PORE DIAMETERS

The determination of pore diameters is relatively straightforward for highly porous materials; it becomes quite difficult with pore diameters less than 1,000 Angstrom units. With materials of larger pore diameter ($d > 0.1\ \mu$), the mercury intrusion technique gives both the pore spectrum and the total pore volume. Unfortunately, mercury intrusion cannot be applied to finer pore systems, particularly those composed of polymers that are pressure-deformable or those in which the porosity depends on the presence of a swelling solvent such as water. Here, the most reliable method is to measure the permeation across the membrane of solute molecules of different size, as first described by Collander*(13)*. Unfortunately, nature has not provided us with an adequate series of spherical molecules of different sizes, ones that do not absorb or otherwise fix themselves to pore walls. Further, as the diameter of the solute molecule approaches that of the pore, the classical hydrodynamic equation of Stokes, as applied to spheres moving in homogeneous media through spherical or rectangular pores by Faxen*(14)*, may be subject to considerable error. The same applies to evaluation of the measurement of air or water permeability, because each pore contributes to the permeability proportional to the 4th power of its radius; a highly distorted average pore diameter may be thus calculated.

Staining of molecular pore membranes by the formation of precipitates, presumably within the pores, has been tried with indifferent results. The staining procedure usually alters the pore structure, but by this technique one may observe the occurrence of large voids, which are difficult to avoid in the formation of many polymeric films. There is considerable evidence that one cannot form precipitates in molecular pores (of the order of 5 to 50 A); these kinds of membranes may, when used as a part of separators, prevent the growth of dendrites through them.

ION-EXCHANGE MEMBRANES

Ion-exchange membranes have been used in several new battery systems. These are films of insolubilized polyelectrolytes, which can contain the sulfonic, carboxylic, phosphinic, phosphonic, sulfate and phosphate acids, amino, and quaternary amine fixed-charge groups*(15)*. Polymers containing other fixed-charge groups, including phosphonium, arsonium, and iodonium, have also been described. The commercial ion-exchange membranes are of the sulfonic acid type for the cation-permeable membranes, and of the quarternary ammonium type for the anion-permeable membranes, because these groups are strongly ionized, are of reasonable chemical stability, and do not form ion-pairs or chelate complexes with metallic ions*(16)*.

The most common polymeric matrix for membranes of this kind is polystyrene; Figure 1 shows diagramatically a typical cross-linked polystyrene sulfonic acid material. The drawing, roughly to scale, indicates that the pore diameters are approximately 10 Angstrom units*(17, 18)*.

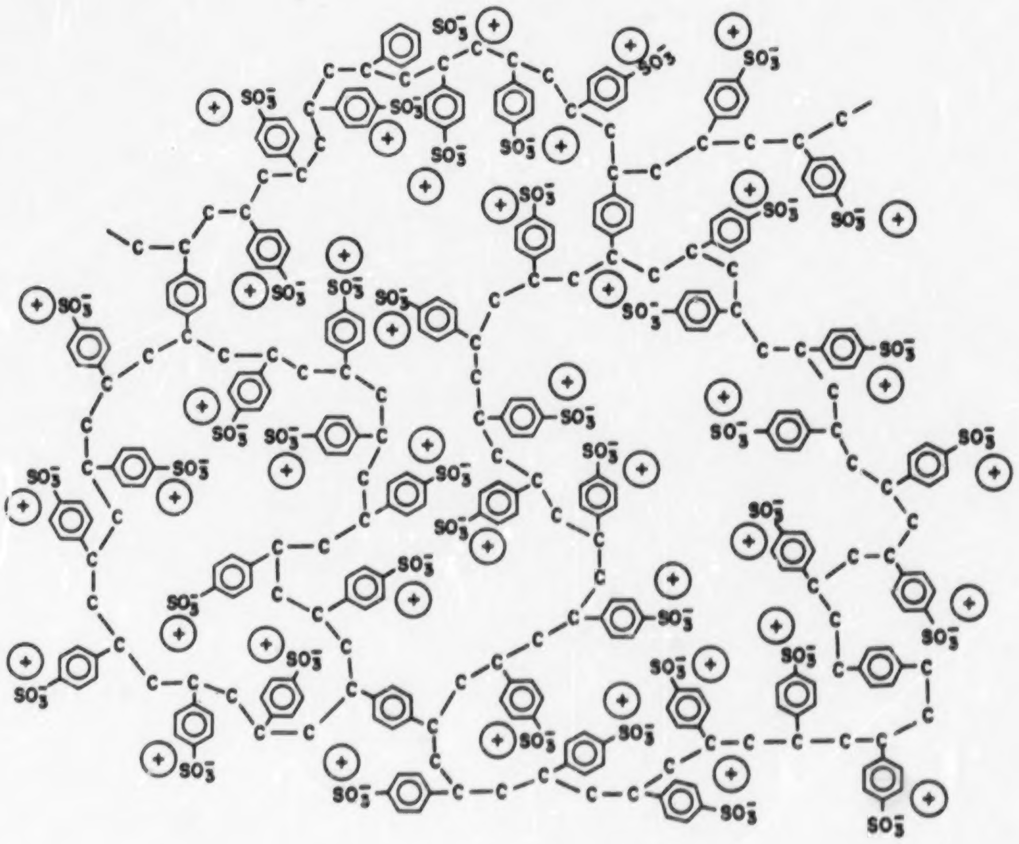

Figure 1. A typical cross-linked polystyrene sulfonic acid material.

Techniques for the preparation of ion-exchange membranes include direct polymerization in sheet form; casting from interpolymer mixtures; and the preparation of heterogenous membranes by suspending ion-exchange resin particles in a matrix polymer and forming a film by extruding or by casting from a solvent. Bieber describes several of the latter procedures*(19)*.

Whereas the stability of cation-permeable membranes prepared from polystyrene sulfonic acid has been suitable (these membranes can be used at temperatures up to 100°C for long periods without severe degradation), the same is not true of the quaternary ammonium anion-permeable membranes, which usually degrade appreciably in weeks or months even at 60°C. The recent synthesis of a substituted pyridinium compound (2, 6 di-t-butyl pyridinium iodide) of unusual stability was reported by Okamoto and Shimagawa*(20)*. These authors treated 2, 6 di-t-butyl pyridine with methyl iodide under high pressure. The compound could be sublimed at 250°C under reduced pressure without decomposition. Its unusual stability might be applied to the preparation of anion-exchange membranes of stability comparable to that of cation-exchange films.

Ion-exchange membranes are selectively permeable either to cations or to anions by virtue of the fixed charges contained therein. The Donnan potential gives rise to an equilibrium that may be expressed in simplified form as follows for a system of fixed sulfonic acid groups ($ReSO_3^-$) in equilibrium with a solution of potassium chloride:

$$[\overline{K^+}]\ [\overline{Cl^-}]\bar{\gamma}_{\pm} = [K^+]\ [Cl^-]\gamma_{\pm};\ [\overline{K^+}] = [ReSO_3^-] + [\overline{Cl^-}],$$

where [ ] is the concentration of the fixed charges expressed in molality or in terms of the imbibed water within the pore, $\gamma_{\pm}$ is the mean activity coefficient, and the superscript bar indicates values pertaining to the membrane phase. Recent studies have shown that this simple equation predicts the behavior of many membrane systems rather accurately if one sets $\bar{\gamma}_{\mp} = 0.45$*(21)*.

The Donnan equation predicts that membrane selectivity will fall with increasing concentration of the ambient electrolytic solution, and this is observed. For maximum selectivity, the concentration or molality of fixed-charge groups within the film must be as high as possible; commercial films having molalities (m) in the range of 5 to 8 exhibit a commensurate ionic selectivity. With highly concentrated electrolytes, however, even these membranes will not be very selective. For example, in 5m potassium hydroxide and a fixed-charge membrane of concentration $5\overline{m}$, the transport number (fraction of current carried by each ionic species) for the permeable ion is but 0.73.

Fixed-charge membranes do not show concentration polarization within the membrane phase, but do exhibit this phenomenon strongly in the adjacent solution phase. For these reasons, fixed-charge membranes are favored for use in fuel cells. When relatively dilute solutions are interposed between the fixed-charge membranes and the electrodes, however, a marked concentration polarization ensus, with an increase in the ohmic resistance of the depleted electrolyte layer adjacent to the membrane phase; other undesirable side effects also occur*(22, 23)*.

When a current is passed across a fixed-charge membrane, the selective transport of one species over another takes place because the concentration of ions of the charge opposite the fixed-charge (counter-ions) is very much greater than that of ions of the same charge (co-ions). In these narrow-pore systems considerable hydrodynamic drag is imposed upon all ions, particularly those whose diameters approach that of the pore. Along with the ionic flux there is a flow of solvent, termed electro-osmosis. The amount of water transported by electro-osmosis increases with the size of the counter-ion and the pore diameter for the "tight" membranes of high selectivity. This solvent transport can be appreciable; for "tight" membranes it is about 100 milliliters per Faraday; in "loose" ones it can be of the order of liters per Faraday. Recent studies by Bagner*(24)* have shown that when the diameters of counter-ions are approximately 80 to 90 percent of the pore diameter, "plug flow" results, and essentially all of the water content of the membrane moves with the counter-ions.

Although this electro-osmotic flow can be used to advantage in some systems, it usually presents a problem to be overcome in batteries separators because the solvent flows with the ionic current. The pressures generated by electro-osmosis are considerable. Electro-osmotic flow is particularly troublesome in fuel cell membranes, in which it acts to dry out one electrode and flood the others. Wicking systems are used to recirculate water under these circumstances.

As mentioned earlier, ions can be made to show marked differences in permeability in certain films, on the basis of differences in their hydrated sizes. A most interesting film has been developed by Yawataya, Oda, and Nishihara*(25)*, who coated the surface of conventional ion-exchange membranes with a very thin (5 μ) layer of a co-condensate of phenol, phenol-sulfonic acid, and formaldehyde, and achieved a transport number of 0.01 for Ca^{++} in a sodium-calcium solution; the latter ion is about twice as large as the former.

The common inorganic ions, particularly the alkali metal cations, demonstrate conductivity in aqueous solution, an indication that they are hydrated to an extent that decreases with the ionic size. Values for non-hydrated and approximate hydrated diameters are given in Table 2. Because the hydration energies are considerable, extensive dehydration of an ion on entering a pore system is not readily achieved. It was observed recently that valinomycin, a cyclic dodecadepsipeptide, has such a very fine and rigidly controlled pore diameter that it can produce a structure more permeable to potassium than to sodium ions by a large factor; this observation shows at least that such systems exist, and they may be the source of the high level of ionic discrimination demonstrated by biological membranes*(26, 27)*. The usual sequence of hydrated volumes is observed in most membrane systems, with the permeability series potassium>sodium>lithium. The markedly higher hydration of the alkali metal divalent ions such as calcium and magnesium has allowed the membranes having very fine pores to show a high selective permeability to univalent over divalent ions*(25)*.

Table 2. IONIC PROPERTIES

	λ°	r in A	Crystal radii, A
H	350		
Li	39		0.68
Na	50		0.98
K	74	2.1[a]	1.33
Me_4N	45	3.47	
Et_4N	33	4.00	
Pr_4N	23	4.52	
Bu_4N	20	4.94	
OH	195		
Cl	76	2.3[a]	1.81
Br	76		1.96
I	77		2.19
SCN	72		
pTS	34		
IO^3	40	3.7[a]	
NO^3	71		

[a] From distance of approach in solution λ° is equivalent ionic conductance at infinite dilution.

MEMBRANE THICKNESS

The thickness of polymeric membranes can be controlled within rather wide ranges. Cast films of a number of common matrix polymers can be as thin as 5 microns and still demonstrate reasonable mechanical strength and the absence of pinholes; the conventional packaging films vary in thickness from approximately 10 to 50 microns. Membranes as thin as 1 micron have been prepared and studied; these are very fragile and require support. One means of support is to cast the film directly onto a thin, fine fabric, as is done with certain commercial ion-exchange membranes. Very thin films having a thickness of approximately 0.1 to 1 micron can be cast directly onto a fine porous matrix such as a treated paper without the introduction of holes. Also, one can apply the techniques first described by Loeb and Sourirajan(28), who cast a film, allowed a thin skin to form as a result of the rapid evaporation of the solvent from the surface layer, and then coagulated the film in a nonsolvent. By the choice of appropriate materials, solvents, and conditions, one can produce membranes having a highly porous and open substructure with a very thin film of the same polymer on one face. For example, films having an effective thickness of approximately 1 to 2 microns on a substructure of some 50 to 100 microns have been prepared.

SOLUTE-BINDING MEMBRANES

Membranes that are impermeable to certain ionic or molecular species can be made by incorporating on their pore walls substituents that react reversibly or irreversibly with the mobile species. A familiar example is the use of cellophane membranes in the silver-zinc battery, in which under alkaline conditions the cellulose reacts with silver ions (or colloidal silver) to form an insoluble, immobilized material. The same type of irreversible reaction may result when rubber membranes vulcanized with sulfur and presumably containing reactive sulfur compounds are used in lead-acid batteries; sulfur-antimony complexes apparently form, and the metallic ions, no longer able to diffuse to the electrode, are "trapped."

The interactions of ionic species with polymers containing specific binding agents have been studied extensively; the polymers have been in solution, in resin, and in membrane form. The original stimulation for this work came from Skogseid(29), who showed that the classical chemical reactions involving aromatic structures can be carried out with linear or cross-linked polystyrene. With systems of these kinds, byproducts that are part of the polymeric structure remain so and cannot be separated; by judicious use of chemical reactions Skogseid prepared a number of materials of rather complex nature. Figure 2 shows a few of the structures that he prepared and characterized. Familiar chelate structures are included.

Gregor, Taifer, Citarel, and Becker(30) prepared a number of chelating ion-exchange resins based upon familiar condensation reactions; extensive studies of polymers containing groups capable of specific interactions with solutes, particularly the transition metal ions, have been reported(31, 32). The general theory of such interactions has been investigated by Wall (33), Gregor(34), Morawetz(35), and others. The rather common carboxylic polymers form fairly strong complexes with the alkaline earth and transition metals; amine polymers form similar complexes with the transition metals. Because of the high local concentration of ligands or complex-forming groupings in polymeric systems, one usually encounters stronger binding with polymeric ligands than with monomeric ones.

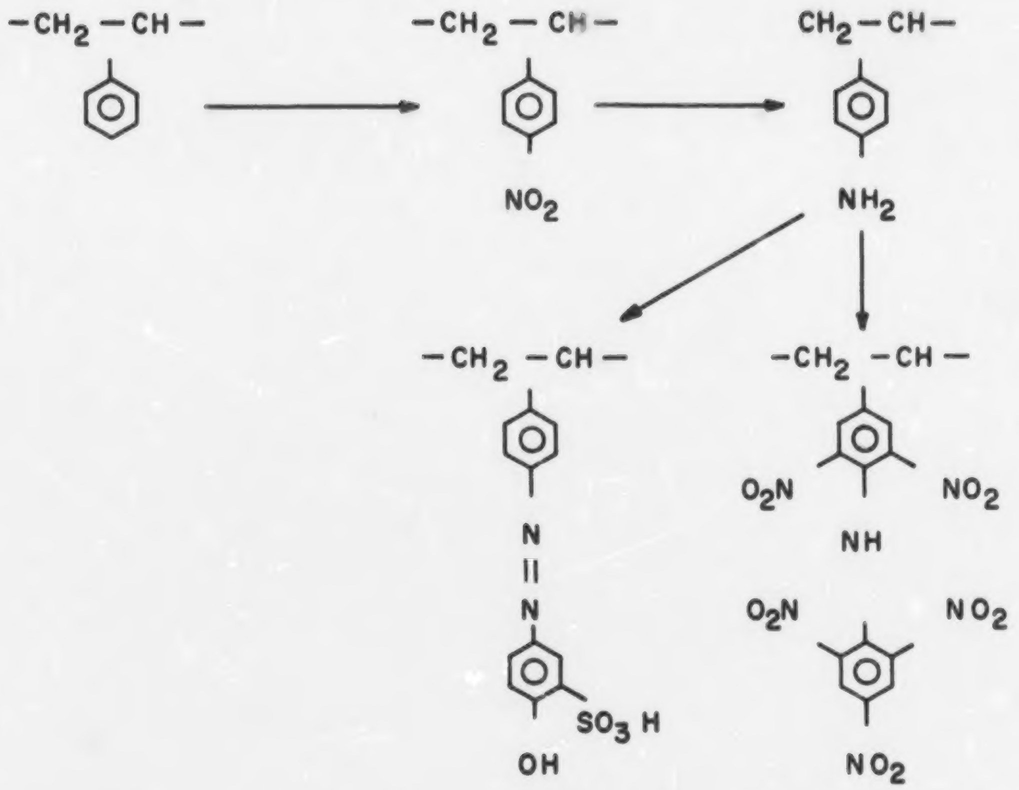

Figure 2. Some of the complex structures prepared by Skogseid (reference 29).

Of particular interest to those concerned with battery technology is the availability of polymers containing the SH grouping, one capable of rather specific interactions, particularly with heavy metals*(36, 37)*. Bayer*(38)* has described an interesting example of a polymeric chelate demonstrating high specificity (Figure 3), with which the extraction of gold from sea water was claimed. Preparing chelate resins or membranes need not entail involved chemical procedures when the monomeric ligand is available. As an example, Gregor and Wallace*(39)* prepared thiourea and phenylthiourea polymers by formation of the condensate (with formaldehyde) as a cage about a hydrophilic polymer to maintain porosity. The final product showed a high capacity of this thiol grouping, one that forms particularly strong complexes with heavy metallic ions, particularly those of silver, mercury, etc. Many other systems are susceptible to this kind of cage polymer formulation.

The formation of metal-chelate complex in membranes acts to bind metallic ions and inhibit their diffusion across the membrane, and although such retardation can result in a considerably lower flux, it is still finite because the reaction is reversible. The work of Wetstone and Gregor*(40)*, in which they studied the relative transport of copper and sodium in a carboxylic membrane, is indicative

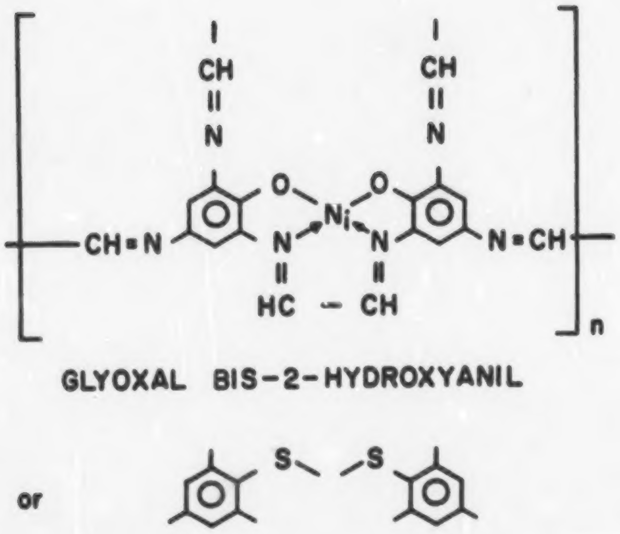

Figure 3. A polymeric chelate of high specificity described by Bayer (reference 38).

of these phenomena. For true "trapping" of the undesirable ionic or molecular species in a membrane, one must use an irreversible reaction, of which several are available. Several oxidation-reduction polymers have been reported by Cassidy*(41)*, Manecke*(42)*, Gregor*(36)*, and Overberger*(37)*. Strong polymeric reducing agents are readily prepared; polymeric oxidizing agents of reasonable stability and oxidizing power are not known at the present time. A particularly convenient and simple procedure for preparing strongly reducing resins (or membranes) was described by Gregor and Beltzer*(43)*, who prepared pyrogallol-formaldahyde co-condensates of a high degree of capacity and porosity.

Electrically regenerable ion-exchange systems have long intrigued investigators. These systems are electronic conductors and contain groups that can be rendered ionic or non-ionic, or at least have a markedly different degree of ionization, as the result of the imposition of an applied electric potential. Weiss*(44)* reported some interesting developments. In principle, such systems would attract anions or cations when polarized (positive or negative), and would discharge these ions when the polarity was removed or reversed. Murphy*(45)* applied this principle for purposes of desalination. Films that were conductive to electrons were prepared by laying down a film of activated carbon onto a metallic grid; the film was then treated with either cationic or anionic polyelectrolytes. Imposition of the potential onto the grid caused the accumulation of either cations or anions; these ions were released by reversal of the potential. The exact chemical reactions that occur are not known; apparently they do not involve a true oxidation-reduction, charge-transfer process but rather a charging process at the surface of the charcoal. Alteration of the ionic charge of weakly acidic groups has been reported by Stillman and Gregor*(46)*, who prepared polymers of the polyacene-radical type with carboxylic groups as part of the conjugated ring system and showed that the acidity of the carboxylic acid group could be increased or decreased by the imposition of a potential from a battery. Although we do not know whether any of these electron-conducting systems can be used in battery separator systems, the possibilities are interesting.

SOLVENT MEMBRANES

We now consider membranes that do not possess pores in the usual sense. These are commonly called solvent-type membranes. A typical film of this type is a familiar cellulose acetate reverse-osmosis membrane first described by Ried*(47)* and then improved by Loeb and Sourirajan*(27)* for use in desalination. These membranes selectively dissolve water and not ions by virtue of the unusual hydrogen-bonded structure of water contained within cellulose acetate. They can have low resistance by virtue of possessing a coherent "skin" of extreme thinness, with a porous substructure for support.

The electrical conductivity of solvent-type membranes, in this case reverse-osmosis membranes of cellulose acetate, has been measured by Saltonstall*(48)*, who has also used the time-dependency of conductivity when the membrane is immersed in an electrolyte solution to calculate diffusion coefficients in the membrane. Results indicated that the equivalent conductance of electrolyte in the membrane did not depend on its concentration in the film. Diffusion coefficents of sodium chloride in typical membranes were about $6x10^{-10}$ square centimeters per second; distribution coefficients $(\overline{m}/m)$ were about 0.1. The membrane resistance increased markedly with heat treatment; for example, resistances of membranes heat-treated at 70°C were 3 orders of magnitude lower than those of membranes heat-treated at 95°C. Resistance of membrane 41 microns thick in equilibrium with 1 M sodium chloride was approximately 6,000 ohms for an exposed area of 1.42 square centimeters. Although this specific conductivity is very low, it is not an unreasonable value for a membrane having an effective thickness of 1 micron. Further, since the concentrations of acids and bases in membranes of these kinds are very much greater than those of salts, these films might prove useful as battery separators under special conditions. The dense packing and the strongly hydrogen-bonded water structure in these systems may allow for much more rapid transport of hydrogen and hydroxide ions than would be encountered in ordinary solution.

The conductivity of acid and base have more recently been measured in cellulose acetate membranes by Saltonstall(*48*). Under these conditions, the equivalent conductivity in the membrane phase is concentration dependent, but not to a very marked extent. When comparisons at the same concentration of all solutes in the solution phase (on a normality basis) were made, it was observed that the specific conductivity with potassium hydroxide was twice that for sodium chloride, and for sulfuric acid was 20 times that for sodium chloride. These results, particularly with acid electrolytes, appear very encouraging.

MISCELLANEOUS MEMBRANES

Thus far I have discussed organic polymeric membranes. Many inorganic membranes do exist, however, and they can provide unusual advantages in that they can be made of materials that allow for a precise and controllable pore structure. Certain ion-exchange minerals show high discrimination for ions on the basis of size, as demonstrated by Hechter*(49)* for sodium-potassium exchange. Inorganic clay membranes were investigated by Marshall*(50)*; membranes of beta alumina*(51)* provide the basis for the operation of the sodium-sulfur battery described by DeWitt in this volume. Synthetic inorganic membranes of a glass-like nature have also been described*(52)*. Membranes made from Vycor glass have been known for some time*(53)*. Inorganic exchanges employed as cracking catalysts may also show a uniform pore structure; the work of Barrer*(54)* and of the group that developed the molecular sieves is pertinent here. Most investigators have been unable to prepare membranes that demonstrate the highly selective properties of these inorganic exchange materials, largely because of the problem of incorporating these into a structure that allows permeation between properly aligned particles.

Kraus*(55)* has described inorganic ion-exchange resins; these and similar systems have been made in membrane form. An example is a cation-permeable film incorporating zirconium phosphate in particulate form; hydrous thorium oxide has served in the anion-permeable membranes*(56)*. Transference numbers of these membranes were 0.90 to 0.96, whereas under the same conditions transference numbers of organic materials were greater than 0.99. Although not highly selective, these membranes operated at high temperature and adverse polarizing conditions for rather long periods without showing some of the defects of the organic membranes. Certain of these inorganic membranes have an intrinsic solubility, which, although very low, can be appreciable under conditions of constant current passage.

Another interesting development has been the availability of separator materials made from polyethylene and capsulated fibers and particles*(57)*. Cellulose fibers have been enveloped with sheaths of polyethylene by the use of transition-metal catalysts, resulting in materials that can be made in membrane form by paper-making techniques. This process is of considerable interest for battery separator applications because it is simple, because particles that can be converted into membrane form are available in large amounts at a low price, and particularly because the porosity of the final sheet can be altered by a further pressing technique.

The special requirements of fuel cells call for development of several different kinds of new separator systems. The ion-exchange membrane electrolyte provides several advantages, among which are ease of fabrication of cells containing a solid electrolyte in the form of thin sheets, resistance to concentration polarization, and the transport of but a single, ionic species. However, organic membranes are susceptible to attack at the electrodes, their electro-osmotic water transport dries out one electrode-membrane interface and floods the other, and the commercial membranes do not possess semi-permeability for different solutes (methanol *versus* water, as an example). The use of fluorinated polymers, even as the matrix polymer, imparts greatly increased chemical stability to the membrane. Further, interpolymer systems now available consist of largely fluorinated materials; these possess even greater chemical stability than the fluorinated polymers. The problem of electro-osmotic water transport is currently handled by various wicking systems; Gregor*(58)* has shown that by the use of a mosaic membrane one can re-transport water electro-osmotically to the dry membrane side.

Finally, there are some new and interesting possibilities for the preparation of membranes that will impede one solvent and not another. For example, more polar films not containing aromatic rings, such as ones prepared from polyvinylsulfonic acid, may be expected to show much more sorption of water than less polar solvents such as the alcohols. The recent announcement that certain helical antibiotic molecules*(26, 27)* can apparently form a channel through which only dehydrated ions can pass suggests that if nature can produce such a highly selective membrane system similar systems possibly can be created in a synthetic structure. Finally, the use of new solvent-type membranes may prove yet another means for controlling the transport of solvents.

HIGH-TEMPERATURE POLYMERS

A recent advance in high polymer chemistry of particular interest to those concerned with battery separator problems is the preparation of many new high-temperature polymers. For more information a collection of papers presented at a recent symposium*(59)* should be consulted, particularly the papers by Atlas and Mark*(60)* and Mark*(61, 62)*. A more recent review by Marvel*(63)* describes later studies.

A few of the new high-temperature polymers deserve mention. An interesting family of linear, rigid polyether-methylenesulfonic materials (PEMS) have been reported by Johnson et al.*(64)*, Karacz*(65)*, Price*(66)*, and Reich*(67)*. These materials are represented by recurring aromatic rings connected in the para-position by sequences of $—SO_2—$, $—O—$, $—CH_2$, $—S—$, or $—C(CH_3)_2$ —bonds. These polymers, particularly the aromatic poly-ether-methylenesulfones have specific gravities of 1.20 to 1.26, a tensile modulus of about 400,000 psi, a tensile strength of about 12,000 psi, and break elongation ranging from 30 to 120 percent. Some of these polymers melt or soften reversibly at about 440°C without degradation if the exposure is short. Viscosities are remarkably constant, even when the polymer is stored at approximately 400°C. Polymers of this type are soluble at high temperatures in certain polar solvents such as dimethylformamide (DMF) and dimethylsulfoxide (DMSO), so they can be readily prepared in film and fiber form.

Another interesting class of high-temperature polymers are the poly-benzimidazoles (PBI) prepared from pre-polymers following the reaction shown in Figure 4, as reported by Gillham*(68)*. Properties of these polymers show very little change at approximately 380°C. Special thermal cures have produced polymers that maintain noticeable rigidity and strength even at 500°C for some time. Mechanical properties of these polymers are unusual; flexural modulus and strength at room temperature are about 4×10^6 and 0.9×10^5 psi, respectively.

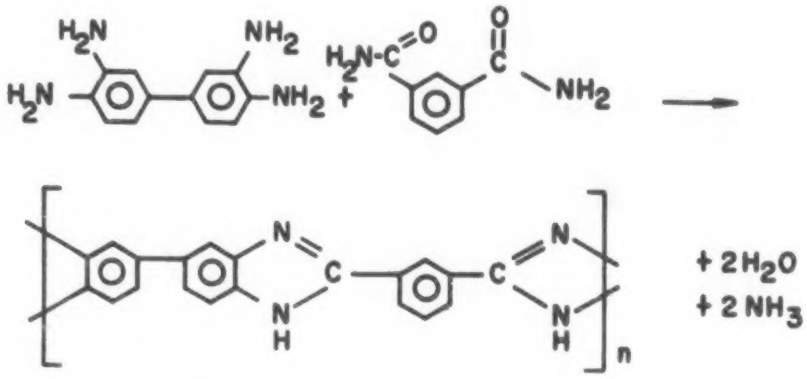

Figure 4. Polybenzimidazoles (PBI) as reported by Gillham (reference 68).

Polyamides containing piperazine are known to be very stable; one member of this family has been studied in some detail, poly (isophthaloyl trans-2, 5-dimethylpiperazine), ITDMP*(69)*. This polymer has a softening range near 400°C; it is soluble in chloroform and formic acid, in which it has high intrinsic viscosities lending itself to film and fiber formation.

Another class of high-temperature polymers, the polybenzimidazobenzo-phenanthrolines (BBB) (see Figure 5), have been prepared by van Deusen*(70)* and Marvel*(71)*. Most of these polymers are soluble in sulfuric acid, benzene sulfonic acid, and concentrated alkalis. When tetra-aminobenzene is used as the basic reactant, the BBL ladder polymers formed are less soluble than the BBB polymers. These polymers do not show weight losses of 5 to 10 percent until heated in air at 550°C

Other high-temperature polymers have been obtained by the oxidative coupling of aromatic diamines. These show the structure

$$[N=N-Ar-N=N-Ar-O-Ar-N=N]$$

where Ar is the benzene ring joined in the *p*-position. Many of these aromatic azopolymers are stable at high temperature; they exhibit no weight loss up to 325°C and only 10 percent weight loss upon heating to 425°C. All of these materials are darkly colored, amorphous, and soluble only in concentrated sulfuric acid at room temperature. The work of Kovacic*(72)*, Preston*(73)*, and Bach*(74)* is relevant.

Finally, two commercially available, high-temperature fibers deserve mention; the first is a poly — 1, 3 — 4 — oxadiazole, and its thiol-analogue, shown in Figure 6*(75)*. This polymer is stable at 250°C and is unaffected by reflux for 48 hours in 10 percent of either sulfuric acid or sodium hydroxide. The second is a poly (phenylene triazole) (see Figure 7); this is stable at 300°C and can be spun from formic acid solutions*(76)*.

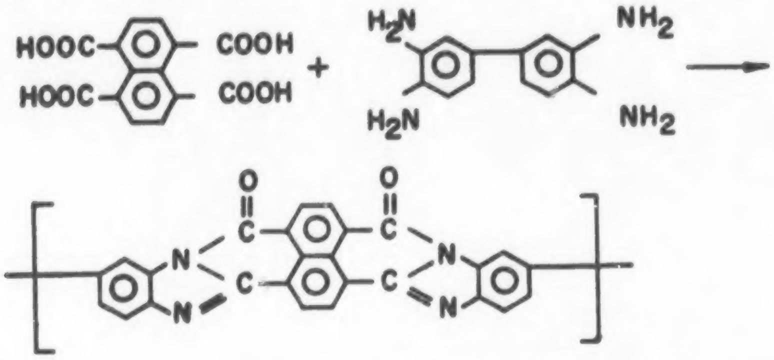

Figure 5. Polybenzimidazobenzophenanthrolines (BBB) prepared by van Deusen and Marvel (references 70, 71).

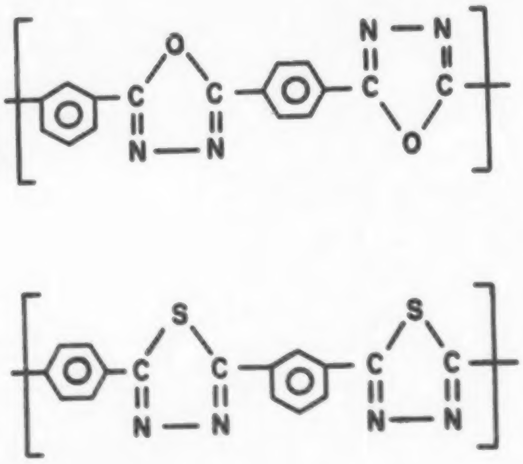

Figure 6. A poly-1, 3-4- oxadiazole and its thiol-analogue (reference 75).

Many new polymers of exceptional thermal and chemical stability will find their way into separator applications, particularly in high-discharge batteries in which the local temperature is high and in fuel cells operated at high temperatures and under highly adverse conditions that ordinarily lead to chemical decomposition.

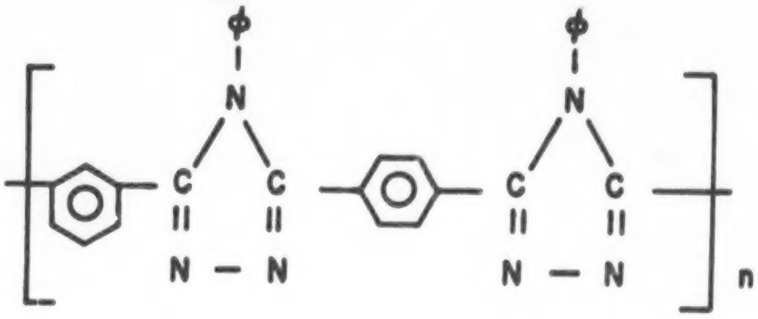

Figure 7. A poly (phenylene triazole) (reference 76).

FIBRIDS

The use of non-woven fibers as battery separators has found some application. A new and particularly interesting development in high polymer technology is the development of "fibrids," a new form of fibers prepared from a number of commercially available polymeric materials. Fibrids can be made from many different polymers in different ways*(77-79)*; in one procedure the polymer is dissolved under high pressure and temperature in a liquid that is a solvent for the polymer under these conditions but is a non-solvent at lower temperatures and pressures. This solution of the polymer is extruded through the spinnerets, upon which the solvent literally boils away, leaving a strand that consists of a very large number of very fine filaments having appreciable mechanical strength but an extremely fine diameter and a large surface area. For example, fibers having a nominal diameter of 25 microns consist of filaments having diameters of 2 to 4 microns, but these are ribbons having smaller thicknesses. Their surface area is of the order of 100 square meters per gram compared to 5 square meters per gram for cotton. Fibrids can be prepared directly from the polymer at a cost of about 50 cents per pound, and one can fabricate them into screens and sheets having a wide range of porosities, a range not ordinarily attainable with fibrous materials. Many applications of these new polymer forms to the battery industry should be forthcoming.

CONCLUSIONS

Battery scientists and engineers have been much too dependent for separator materials on commercial films prepared for other purposes, such as packaging and water treatment. The amount of material needed for membranes usually is so small that manufacturers and fabricators of plastics have not been encouraged toward research and development.

Further, research has tended to concentrate separately upon separator materials or upon electrodes and their interaction with electrolytic solutions, but not upon the combined system. A fundamental investigation of electrode reactions in the presence of well-characterized separator materials should lead to systems of far-reaching practical importance.

We may anticipate the development of several new and vastly improved separator systems based on the new materials and technology available today. The complexity of battery systems, particularly for electric vehicles, requires an interdisciplinary approach, with close collaboration on the part of those who synthesize polymers, prepare them in membrane form, study their structure, and finally incorporate them into practical battery systems.

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NOTES ON A CARBON DIOXIDE SCRUBBING SYSTEM

Harry P. Gregor

Fuel cells that employ alkaline electrolytes and air as one of the fuels all suffer from one common problem — the carbon dioxide in the air converts the hydroxide to carbonate with a loss in power output. The usual remedy is to pass the air through a solution of base, with periodic replacement. This adds to the volume of the power unit, and increases its overall chemical requirements. I would like, therefore, to mention some recent studies on a carbon dioxide scrubbing system that may provide a practical answer to this problem.

Traditionally, acidic gases such as carbon dioxide have been removed by chemical scrubbers; those that use monoethanolamine are typical. Here, an acid base reaction removes the acidic gas, and the absorbant is regenerated by heating because the equilibrium is shifted towards the uncombined reactants at elevated temperatures. The technology of liquid scrubbers is well advanced; these systems have found large-scale applicability, as in the removal of carbon dioxide from gas streams of the ammonia process.

The MEA (monoethanolamine) and analogous scrubber systems have certain advantages and some rather serious disadvantages, particularly when applied to the electric vehicle. The amine is inexpensive, but it is subject to thermal decomposition. Further, amine odors are noxious and they can be somewhat toxic. Ethanolamine scrubbers have substantial heat requirements for thermal regeneration because for every pound of carbon dioxide removed a substantial number of pounds of water must be evaporated. Although this water can be recovered, the heat loss involved is large and the water recovery system must have an appreciable volume.

The use of polymeric amines for removal of carbon dioxide has been investigated. The reactions of polymeric amines with carbon dioxide have also been investigated (Gregor and Robins, 1959; Robins, 1959); the applicability of several polymeric amines for the removal of carbon dioxide from the the air of submarines and space vehicles has been investigated (Gregor and Robins, 1959; Robins, 1959; Weber, 1966; Weber, Miller, and Gregor, to be published). Polymeric amines possess certain important advantages over MEA and its analogues, and certain relative disadvantages. First polymeric amines are much more stable than their monomeric analogues, particularly the ethanolic-substituted amines that are employed because of their reduced volatility compared to the aliphatic amines. Polymeric amines also show a higher thermal stability and are more resistant to air oxidation (Gregor and Robins, 1959; Robins, 1959). The stability of polymeric amines varies; the tertiary alkyl amines are relatively stable; for example, poly-N-methylethyleneimine is considerably more stable than polyethyleneimine (PEI) or polyvinylimidazole. The recently reported polymeric amines of Gianinni (1967) promise to be even more stable.

Polymeric amines cannot be employed in aqueous solution as is MEA because of the considerably greater viscosity that obtains. However, there is no advantage in employing liquid scrubbers in the electric car; it is, rather, advantageous to use these polymeric materials in the solid form. Under these circumstances, the amines absorb relatively small amounts of water, with the amount varying with the relative humidity of the ambient air. On regeneration, only a relatively small amount of water must be evaporated; thus, heat consumption is drastically reduced. Further, polymeric amines have no odor, and thus their employment in limited space would not require an after-scrubber of acid, as is used to remove MEA vapors under these circumstances.

The principal disadvantage of polymeric amines in the solid state is their low rate of reaction, which is controlled by the diffusion of carbon dioxide in the solid polymer to the fixed amino groups. The reaction has been measured (Gregor, Weber, and Miller, to be published) and found to be approximately 10^{-8} square centimeters per second for films in equilibrium with air at 100 percent relative humidity. At lower relative humidities the process is somewhat slower and equilibrium not so favorable; both the rate of absorption and the capacity are approximately halved at 50 percent relative humidity.

Another of the advantages of polymeric amines is the fact that their basicity can be controlled, within appreciable ranges, by the incorporation of salts within the solid phase. Table 1 lists data on the capacity of a PEI-epichlorohydrin condensate for carbon dioxide as a function of the gas content in air, its relative humidity, and its temperature, taken from the dissertation of Weber (1966).

Since the rate of absorption of acid gases by solid-state polymeric amine scrubbers is controlled by diffusion in the solid, thin film or fiber absorbers having a maximum area-to-volume ratio are desirable. The capacity of units designed with different ribbon diameters, based upon the work of Gregor, Miller, and Wolfe (to be published) is given in Table 2 and emphasizes this point. For particularly rapid rates of absorption, the use of solid-state polyamines in the form of fibrids (Morgan, 1961; Blades and White, 1963 and 1966) would offer special advantages.

In operation, a polymeric solid-state scrubber would consist of two filter units operating alternately to produce a continuous stream of air free of carbon dioxide. The ambient air would pass through the filter bed and be fed to the fuel cell, with its composition unaltered except for acidic gases. If appreciable levels of sulfur dioxide and other acidic gases were present, these would also be removed.

Other acidic gases would interfere with the fuel cell reaction, and their removal would be in direct proportion to their acidity. When the filter was exhausted, it would be sealed by the closure of a pressure valve and heat would be applied to the unit (probably employing the excess heat generated by the cell); the acid-base reaction is reversed and almost pure carbon dioxide would be released to the atmosphere, with an air condensor retarding the evaporation of water.

This is not to say that polymeric scrubber systems are fully developed. The capacities for removal of carbon dioxide listed earlier

Table 1. REACTION OF PEI RESIN WTH CARBON DIOXIDE

Temp, °C	CO_2 in atm, %	Relative humidity, %	Capacity, m-moles/g
0	1.0	100	4.1
	0.30	100	1.8
20	1.0	100	2.9
20	0.65	100	2.2
20	0.30	100	1.3
20	1.0	70	1.8
20	1.0	55	1.0
40	0.30	100	0.45
70	0.30	100	1.1

Table 2. ABSORPTION OF CARBON DIOXIDE BY POLYAMINE FIBERS AND FILMS

Fiber or film thickness, μ	% Theoretical capacity	Space between films or fibers, μ	Bed vol, ft³	Cycle time, min.	% Removed on one pass
150	50	50	16	60	20
150	25	25	9	20	30
75	25	25	5	10	30
38	50	25	5	15	20
38	13	25	5	5	40

Conditions: Air at 25°C, 50 percent relative humidity, 0.5 percent Co_2; for CO_2 removal, 15 pounds CO_2 per hour.

are for levels of 0.5 percent, and at 0.05 percent (the usual air level) the capacities would be lower by a factor of about 10. This capacity could be increased, however, by using more basic polymers. It is obvious that several problems must be met, but the availability of a heat-regenerable scrubber system would make alkaline fuel cells more practical for electric vehicles, particularly for military vehicles.

For the Union Carbide (private communication with G. E. Evans) alkaline electrolyte fuel cell, air at a nominal carbon dioxide content of 0.03 percent is scrubbed to an 80 to 90 percent removal level by a caustic solution; without such scrubbing, the cell electrolyte must be replenished 5 to 10 times more often, but this really transfers the problem from the cell solution to the scrubber solution. A 100-watt cell employs from about 500 (4 times the theoretical) to 1,250 liters of air per hour. For a military vehicle, one needs 1 to 10 kilowatts and even higher level power sources. Therefore, a 1-kilowatt fuel cell would, on the average, use 5,000 liters of air per hour or require the removal of about 0.1 pound of carbon dioxide per hour. From Table 2, at a bed volume of 5 cubic feet at a cycle time of 15 minutes for 15 pounds of gas removed per hour at the 0.5 percent level, this amounts to a bed volume of about 0.3 cubic foot for the removal of 0.1 pound of gas at a concentration level of 0.05 percent. This figure may have to be increased somewhat to reduce exit carbon dioxide levels to 10 percent of inlet values.

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BATTERIES AND FUEL CELLS: *status of current research on specific energy-storage systems; how they perform.*

I have been thinking about the oft-recurring circumstances under which the battery industry has responded to the needs for batteries. This industry has been at the threshold of the new in science since 1800, when Volta's pile was announced in England, an event that inpired and inaugurated a golden era of science. Within 30 years came many discoveries about electric current: Oersted on magnetic effects, Ampere on electrodynamics, the Seebeck effect, Faraday on conversion of electric current and his discovery of induction.

On the electrochemical side, Davy had isolated the alkali metals by 1806. Nicholson and Carlisle demonstrated the phenomenon of electrolysis in 1800, and by 1905 Izarn applied it as a coulometer. Believe it or not, Grotthus had formulated his theory by 1806. Electrodeposition of metals was demonstrated and an electrochemical telegraph was in the process of development. In all of these events, the laboratory needed batteries, the only known source of current at that time. It was soon found that the Volta pile was most easily built in fairly large size by using the metals, zinc and copper. Practical problems were encountered in scaling up, and especially in the creation of convenient and easily handled installations.

Within 1 year the people who worked with these larger batteries had already found that atmospheric oxygen improved the performance of this particular cell. This observation has been discovered and rediscovered any number of times in the last 170 years. This period may be said to have culminated in Faraday's announcement of the laws of electrolysis. In all of this, electrochemistry and science and batteries were and are intertwined. Battery technologists find that their problems in making advances to meet demands are always at the verge of the unknown and incompletely understood. For example, they are pestered by lack of understanding of the structure of their active materials, especially with regard to the amorphous materials. They constantly watch for each new material that may extend the range of application for practical batteries.

The same philosophy applies now to the people who enter and become part of the battery industry. We see a widening expanse of the technologists' training, for the battery problems encompass practically every branch of scientific and engineering effort. I believe that the battery industry welcomes this increasing horizon, this broadening of its views, and the edge that it brings in competitive spirit.

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LEAD-ACID BATTERIES AND ELECTRIC VEHICLES

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INTRODUCTION

For the past 50 or 60 years the lead-acid battery has been predominant in the field of battery electric motive power. Today the span of battery propulsion covers conventional submarines, small submersible vessels, industrial trucks, railway cars, mine locomotives, delivery vans, and golf carts. In the past the list would also have included passenger cars. Today we are focusing on electric street vehicles, which include the no longer practical passenger vehicle and the near marginal delivery van.

There are literally dozens of different types and sizes of lead-acid batteries on the market — each designed for a specific application. Many of these are being used for electric propulsion. Four of the most important are flat plate motive power; tubular motive power; golf-cart; and starting, lighting and ignition (SLI) batteries.

Flat Plate Motive Power Cells

For many years flat plate motive power cells have been the standard of the industry for rugged service in industrial truck and mine locomotive applications. Figure 1 shows the important electrical characteristics of a typical cell. A battery of six such cells in a steel tray delivers 5.0 kilowatt-hours and weighs 576 pounds (8.7 watt-hours per pound). In average service this battery lasts for 6 to 7 years, giving about 2,500 cycles before the capacity drops to 80 percent of its rated value.

Tubular Plate Motive Power Cells

For certain applications where volume is at a premium, e.g., narrow-aisle fork-lift truck, cells with tubular positive plates are widely used. Figure 2 shows the electrical characteristics of one of the most popular sizes. A battery of 18 such cells in a steel tray delivers 20.8 kilowatt-hours and weighs 1,944 pounds (10.7 w-hr/lb). The service life may be somewhat shorter than that of the flat plate battery, but still amounts to 5 to 6 years and about 1,800 cycles.

SLI Batteries

These are familiar to all as the electrical energy storage device in the electrical system of all automobiles. Being relatively low in cost and readily available, SLI batteries are frequently used for experimental electrical vehicles. Important electrical characteristics of a common size are shown in Figure 3. The ampere-hour rating of SLI batteries is specified at the 20-hour rate — quite unrealistic for motive power applications. Further, these batteries are designed to deliver large currents for engine starting and to withstand constant overcharge whenever the engine is running. These factors combine to make the SLI battery unsuitable for the deep discharges associated with motive power service. The life of a first-quality SLI battery used to power an electric vehicle might be less than a year (100 to 200 cycles).

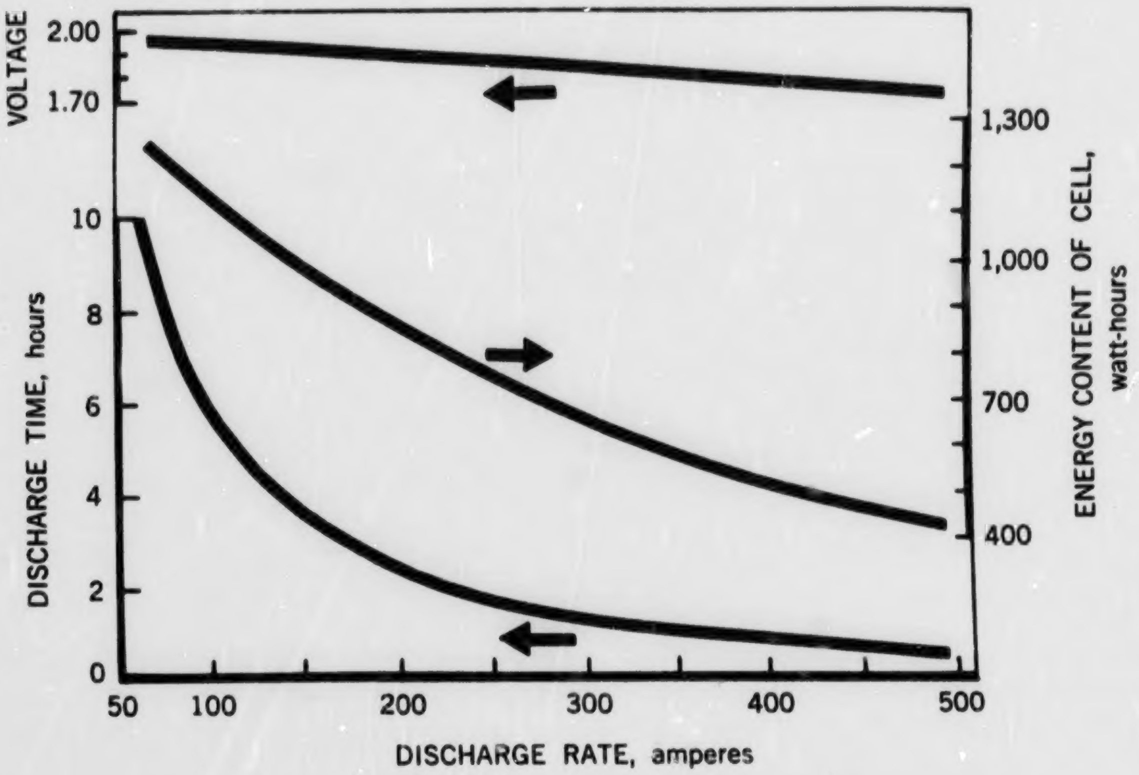

Figure 1. Discharge characteristics of flat plate industrial battery (GNB type 72X-13, 1.280 SP. GR., 77°F, 81 lb per cell).

Golf-Cart Batteries

Golf-cart batteries would seem to be the closest approximation to an electric street vehicle lead-acid battery. Two versions of such batteries are on the market. One is based on industrial battery technology and has tubular positive plates. Presumably it will give service similar to that quoted for tubular plate cells. By far the more common version of the golf-cart battery is based on SLI battery designs. The principal differences are larger and thicker plates and more effective plate separation. Figure 4 gives the electrical characteristics of this battery. At the 5-hour rate the energy density is 14 watt-hours per pound and 1.8 kilowatt-hours per cubic foot. A

750-pound (curb weight) golf cart with 180 pounds of battery has a maximum speed of 20 mph and a range of approximately 30 miles. Properly serviced batteries last 1 to 2 years.

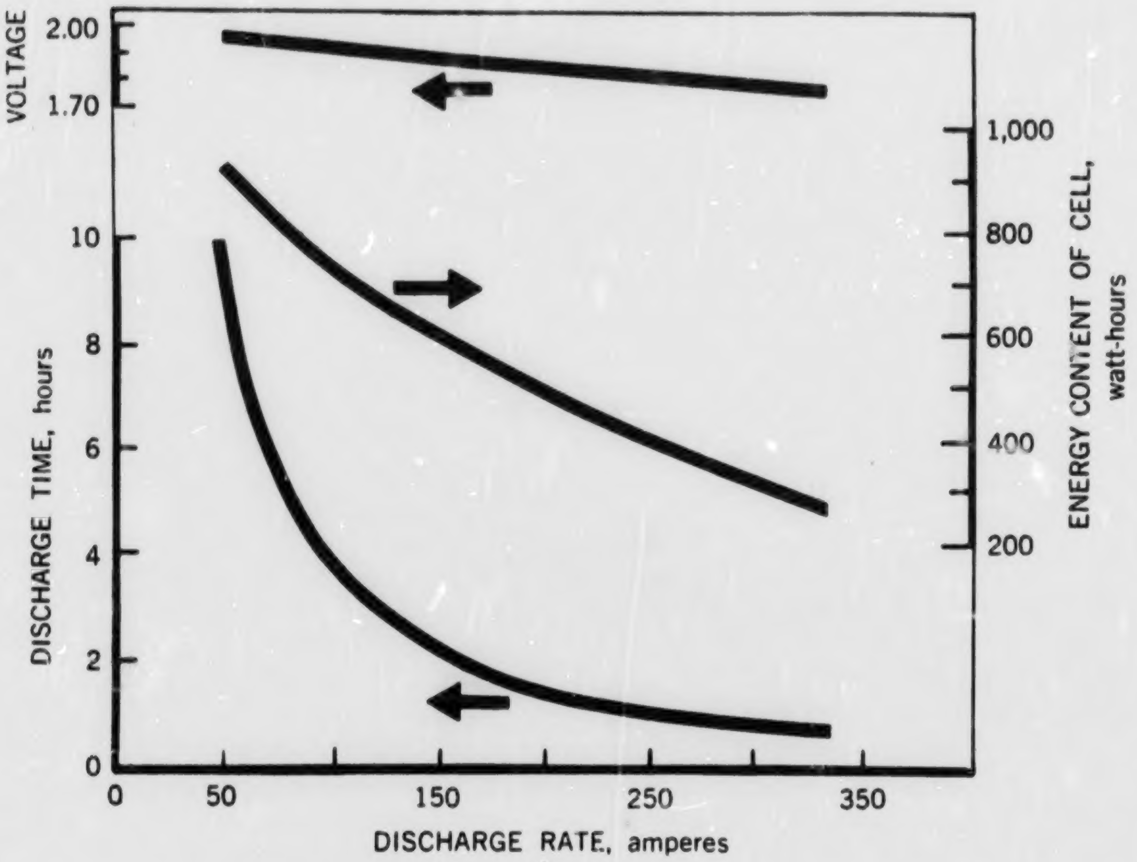

Figure 2 Discharge characteristics of Tubular-plate industrial battery (GNB type 85T-15, 1.280 SP. GR., 77°F, 85 lb per cell).

ELECTRIC STREET VEHICLES TODAY

The relatively modest energy-storage capability of the lead-acid battery and the resultant "poor" performance of electric street vehicles incorporating them has been the subject of much discussion in the technical and public press in recent months. It is instructive to document this as point of reference. The two examples that I will discuss both incorporate motive power lead-acid batteries.

The first is electric street delivery trucks manufactured and sold by Gould-National Batteries, Inc., 10 to 12 years ago. Altogether some 50 were made and sold and 10 or more are still giving satisfactory service in New York City. Table 1 gives some pertinent characteristics and performance figures.

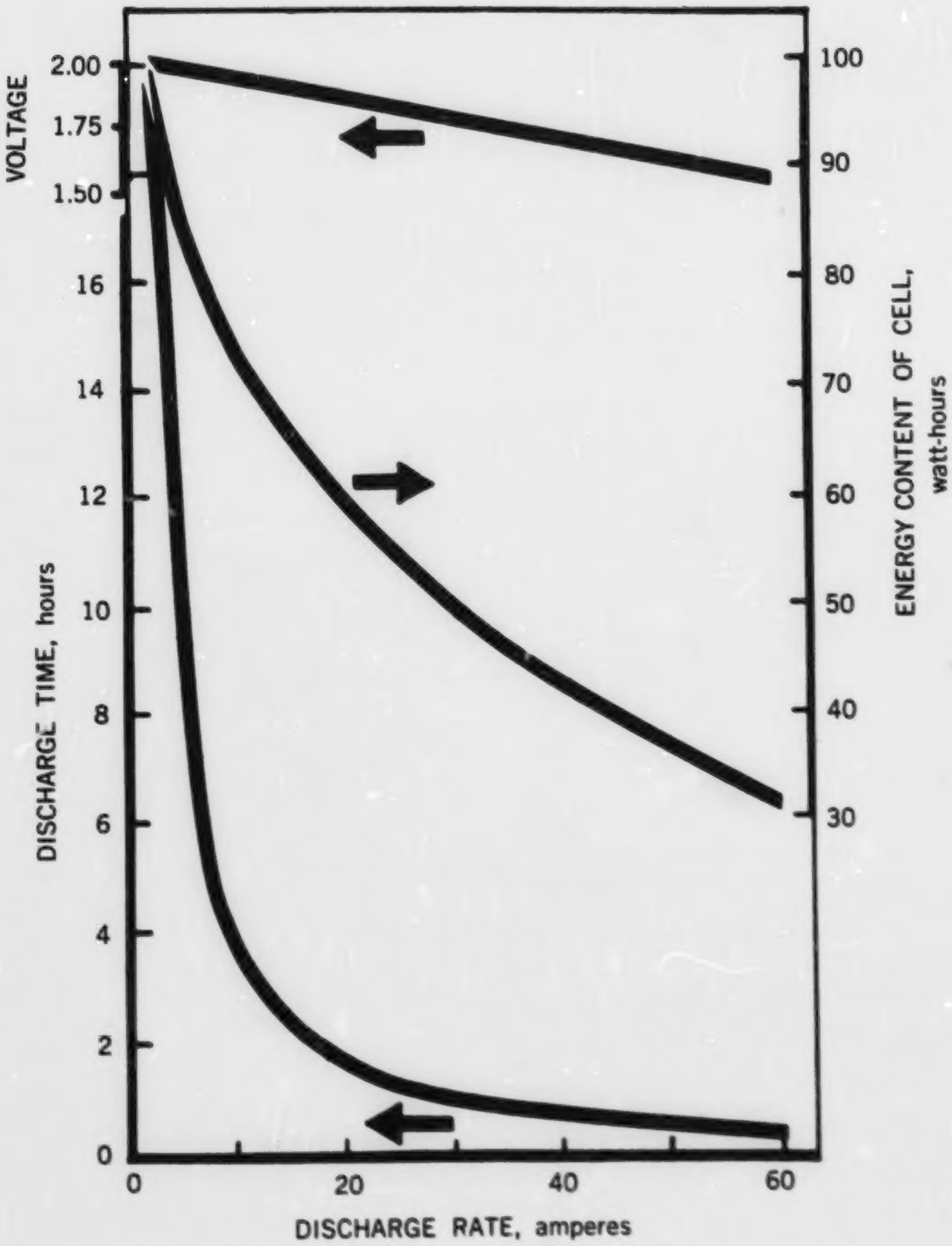

Figure 3. Discharge characteristics of SLI battery (1.280 SP. GR., 77°F, 42 lb per battery).

For the second example I have chosen one of the many small passenger cars that have been converted to battery electric propulsion. This is the "Mini" Traveller, converted to electric drive by the Traction Division of A.E.I., Ltd., in the United Kingdom (Jeremy, 1966). Table 2 describes the characteristics and performance of this vehicle.

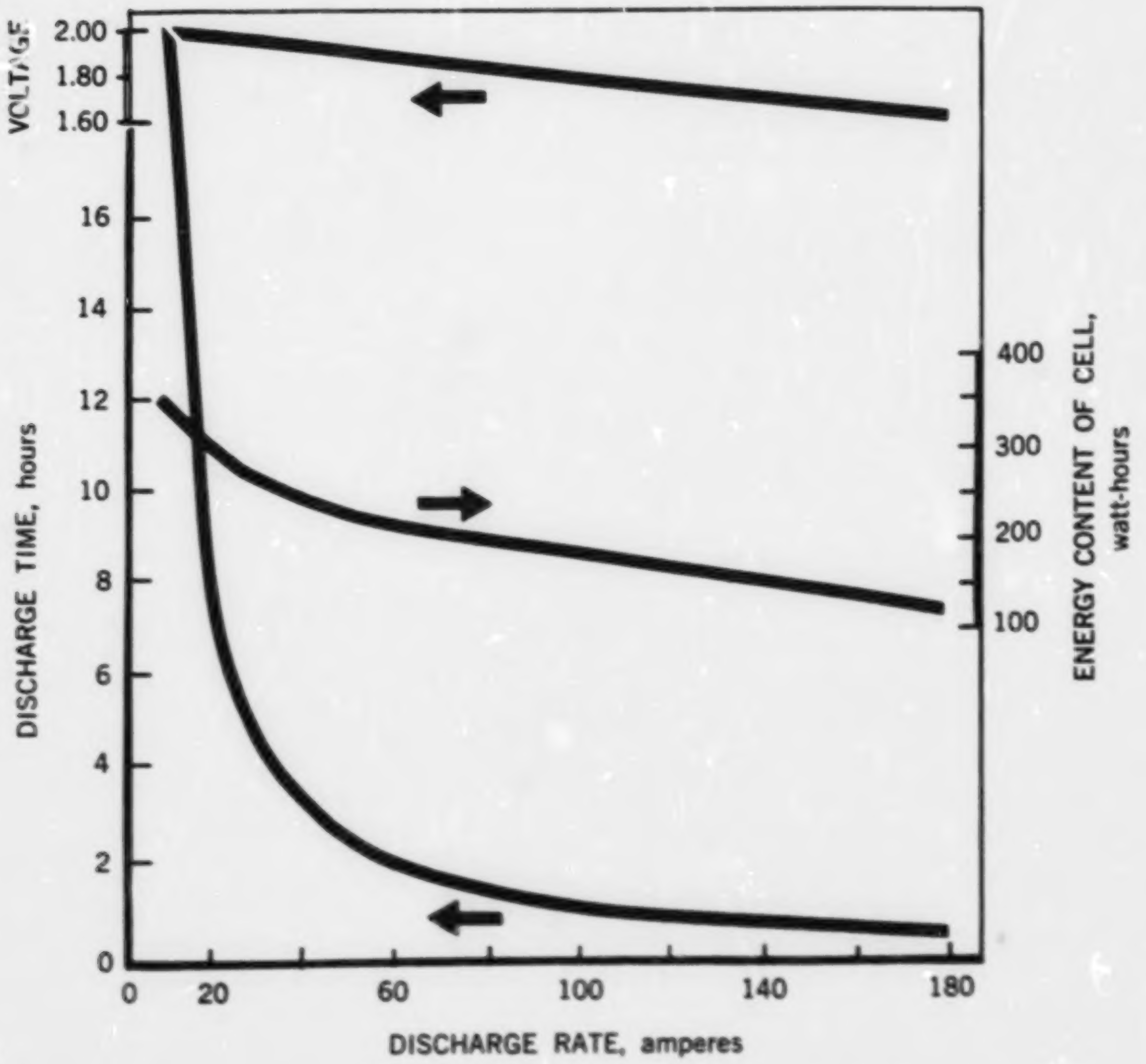

Figure 4. Discharge characteristics of golf-cart battery (1.280 SP. GR., 77°F, 62 lb per battery).

Table 1. CHARACTERISTICS OF THE GOULD "ELECTRUK" (1.5-ton capacity)

Curb weight, lb	9,500
Lead-acid battery weight, lb	2,450
Payload, lb	3,000
Maximum speed, mph	18
Range (multiple stops), miles	20
Battery capacity (5-hr rate), kw-h	23
Controls	Series — parallel switching

Table 2. CHARACTERISTICS OF THE ELECTRIC DRIVE "MINI" TRAVELLER

Curb weight, lb	2,500
Lead-acid battery weight, lb	829
Payload, lb	500
Maximum speed, mph	41
Range (constant 30 mph), miles	37
Range (4 stops per mile), miles	16
Battery capacity (6-hr rate), kw-h	9.6
Battery capacity (1-hr rate), kw-h	6.4
Controls	SCR

These examples, and many more that could have been chosen, lead to the not-surprising conclusion that electric street vehicles powered by industrial lead-acid batteries have performance characteristics much below those of gasoline-engine-powered vehicles. This leads to the question of what improvements in vehicle performance might be expected in the near future from projected advances in the design of lead-acid batteries.

IMPROVED LEAD-ACID BATTERIES FOR ELECTRIC VEHICLES

The first consideration here is simply that the vehicles just described, and all others of which I am aware, have "made do" with available batteries. With the possible exception of the golf-cart battery, no battery has been designed for this service in terms of electrical characteristics, size and shape of cells, and life. When the battery is designed as part of the total vehicle system, appreciable improvements in performance for the same weight may be expected. Further, recent advances in plastic technology have made possible reductions in weight of containers and connectors amounting to 10 percent of the total weight of a golf-cart battery, for example. By proper plate design, making use of the recent development in ancillary technology and designing the battery for the vehicle system, it is anticipated that the energy density (kw-h/lb) may be increased by 30 to 40 percent over that in industrial motive-power batteries. Some sacrifice in life will be entailed.

Gould-National Batteries is undertaking the design and prototype manufacture of a lead-acid battery optimized for the electric-street-vehicle application as we understand it. The first attempt at this has given us a battery on paper that will deliver somewhat over 18 watt-hours per pound at the 5-hour rate. Applied to the Gould

"Electruk" the total capacity of the battery would be over 50 percent greater. Similarly, the "Mini" Traveller would benefit from a 25 percent increase in battery capacity. The life of this battery is designed to be between that of the rugged industrial motive-power battery and the golf-cart battery, i.e., 3 to 4 years.

None of this is particularly spectacular when compared with battery systems described elsewhere in this volume; however, this optimized electric vehicle battery is characterized by being within reach of present-day technology — no breakthroughs are required. One other consideration deserves emphasis, the matter of cost.

CONSIDERATIONS OF BATTERY COST

I will take it as established that operating electric street vehicles will cost substantially less than operating gasoline-engine-driven vehicles (Jeremy, 1966; Hoffman, 1963; Hender, 1965). Here I want to treat the costs of battery energy sources in a very generalized way. The price of the most popular automobiles today falls between 50 and 75 cents a pound (Hoffman, 1963). SLI batteries, which are manufactured in quantities of 40 million or more per year, are priced to the consumer at about 50 cents per pound. Industrial lead-acid batteries, which are manufactured on a job-shop basis, are priced at an average of about 70 cents per pound. On this rough basis the price of lead-acid batteries is at least consistent with that of automobiles. Translated into dollars of initial cost per unit of energy, SLI and industrial motive-power batteries sell for approximately $35 and $70 per kilowatt-hour, respectively. Using Reid's (1966) estimate of 20 kilowatt-hours as being required for minimum acceptable performance we can reasonably project that in mass production a lead-acid battery for an electric vehicle will sell for between $700 and $1,400. Other types of batteries, some made on a large scale today, are priced at from 2 to 20 times the higher of the above values. One must conclude that the price structure of the lead-acid battery only will in the near future lend itself to an attractively priced electric passenger vehicle.

CONCLUSION

My conclusion, which does not differ radically from that of many others who have discussed this subject, is that for the next 5 to 10 years only the lead-acid battery will be used in significant numbers of electric street vehicles. Passenger vehicles will perform better than the current "research" vehicles but their performance will be marginal compared to that of gasoline-engine-powered automobiles. Delivery trucks may fare better if urbanization trends continue. I am sure that I speak for the entire lead-acid battery industry in saying that every effort will be made to improve and optimize this most useful of battery systems for the electric vehicle.

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HIGH-ENERGY NON-AQUEOUS BATTERY SYSTEMS FOR ELECTRIC VEHICLES

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INTRODUCTION

In the past decade the desirability of electric vehicle propulsion has become increasingly recognized. Although the concept is far from being new and was somewhat popular after the turn of the century, it was essentially completely eclipsed in the lata 1920's and 1930's by the rapid advances of the gasoline-powered automotive engine. The renewed interest in electrically driven vehicles can be attributed to the following motivations:

1. The advances in electrochemical power sources, e.g. high-energy batteries, fuel cells, metal-air cells, etc., have progressed to a point where energy densities required for reasonable vehicle speed and distances appear to be in sight.
2. The large increase in air pollution in urban areas throughout the world has placed the long-range acceptability of a hydrocarbon engine in question. This is particularly aggravated by the anticipated growth in the demand for passenger vehicle transportation.
3. The consumer prices for gasoline rising proportionately faster than the cost of electricity puts greater weight on the exploration of fuel cell power supplies for vehicles for better fuel utilization efficiency, and on the desirablity of employing storage battery operated vehicles, recharged overnight with cheap off-peak power.
4. The progress in the design and efficiency of electric motors in recent years has resulted in a considerable reduction of their weight.
5. Advances in circuitry and semi-conductor devices offer the opportunity for better utilization of the power on changing loads without appreciable waste of energy.

In order to appreciate the importance of the lithium high-energy non-aqueous battery system and to gain a better perspective of its function and the spectrum of possibilities for vehicular propulsion, it is of interest to examine briefly all other electro-chemical power sources that can at least potentially be considered for this purpose and to analyze their relative merits and disadvantages. An examination of possible power sources rapidly reduces the possibilities to the following six:

1. Fuel cells operating on a storable fuel and using air as a cathodic depolarizer (oxidizer).
2. Electrically regenerative fuel cells, i.e., devices fundamentally analogous to a storage battery.
3. Metal-air hybrid cells.
4. Rechargeable battery systems of the aqueous type (room temperature).
5. Rechargeable battery systems of the fused salt type (high temperature).
6. High-energy battery systems of the non-aqueous type (room temperature).

Before examining the potential applicability of any devices within the above six classes to the problem of electric vehicle propulsion, it might be useful to review briefly the technical and economic requirements that these electrochemical sources would have to meet.

The most important question, aside of the problem of the torque characteristic of a direct-current motor, which will not be discussed at present, is the general disparity between maximum advertised horsepower and the brake horsepower of today's automobiles. Only 60 percent of the advertised horsepower (Hoffman, 1962 and 1966) is left available as brake horsepower to overcome the aerodynamic drag and the tire drag, and to provide for acceleration. Considerations of this type lead to the conclusion that a compact-type passenger vehicle can be conceived with a direct-current motor in the range of 20 to 30 brake horsepower. If we assume an average electrical load of 20 kilowatts, an average vehicle speed of 40 mph, and a reasonable distance range goal of 200 miles between refueling or recharging, it is obvious that an energy storage capability of 100 kilowatt-hours is necessary if the electric vehicle is to be something more than a curiosity item or a convenience cart.

There are considerable savings in weight when one converts from internal combustion engines to electric propulsion. It has been estimated in one case that as much as 49 percent of the electric automobile's weight could be in batteries (Hoffman, 1966). Since this figure may be somewhat optimistic, we shall assume a more conservative figure of 30 percent for a 2,400-pound vehicle. This would provide for a battery or fuel cell system allowance of 720 pounds. For a storage of 100 kilowatt-hours of energy, this means an energy density of at least 140 watt-hours per pound per cycle. The emphasis is on the words "per cycle" since it is obvious that for a rechargeable system this energy delivery must be obtained to whatever percentage depth of discharge is necessary in order to provide for a reasonably good, i.e., economical, cycle life. A range of 200 miles is considered a reasonable minimum to meet the performance requirements to which modern man has become accustomed. The vehicle also must have enough power level, as discussed previously, in order to reach top speeds if the vehicle is to qualify for admission to parkways and freeways.

Thus, in summary, in considering electrochemical power sources as potential candidates for electric vehicle propulsion, we shall look toward those capable of meeting an energy density of about 140 watt-hours per pound, or preferably more. There are other criteria that must of course be employed in the analysis of the suitability of the many electrochemical devices that can be proposed. These include the cost of fuel per mile or per kilowatt-hour, the cost of equipment amortization over its useful life, the associated safety problems, the startup and shutdown procedure requirements, maintenance considerations, and availability of recharge or refueling facilities. It is difficult within the scope of this paper to deal with all of these aspects. It is for this reason a limitation will be made to the considerations of the following three criteria: energy density, cost per mile, safety, and public acceptance.

FUEL CELLS

There are many different types of fuel cells under development, some using hydrogen or other gaseous reactants, others using storable fuels. Although these systems have different characteristics, one fundamental aspect common to all fuel cells, unfortunately and surprisingly enough, is not being recognized. The fundamental problem is that a fuel cell must be regarded as an electrochemical or galvanic engine, that unfortunately has a high ratio of weight to power, compared to the internal combustion engine. The superiority of a fuel cell comes through in a shining manner when small amounts of power are required for a long period of time. Then its inherent efficiency resulting from the galvanic energy conversion (free of any Carnot cycle limitations) results in the achievements of high-energy-density ratios in terms of watt-hours per pound.

It really matters little what the anodic fuel in a fuel cell is, as far as the weight of the fuel cell plant itself is concerned. It may therefore be convenient to examine the data shown in Table 1, which considers a 20-kilowatt hydrogen-air fuel cell operating at an over-all efficiency of 60 percent. On the basis of near term technology, a rather optimistic weight of 1,850 pounds was assumed for the fuel cell itself, including controls but excluding tankage of fuel. In this system there is no weight penalty for the use of oxidant since air would be used and only an air compressor has to be considered. This weight of 1,850 pounds is based on anticipated technology resulting from current work on the Gemini and Apollo fuel cell programs and compares rather favorably with the 3,380-pound weight of a 32-kilowatt fuel cell employed in the recently demonstrated General Motors Electrovan.

Table 1. 20-KILOWATT HYDROGEN-AIR FUEL CELL POWER PLANT FOR VEHICULAR PROPULSION[a]

Fuel cell and controls weight	1,850 lb (Near-term technology)					1,410 lb (Long-term technology)				
Mission duration, hours	5	10	24	100	200	5	10	24	100	200
Vehicle range, miles	200	400	960	4,000	8,000	200	400	960	4,000	8,000
Total energy storage, kw-h	100	200	480	2,000	4,000	100	200	480	2,000	4,000
Total system weight, lb	1,898	1,939	2,024	2,782	3,624	1,448	1,489	1,584	2,292	3,174
Overall mission energy density, w-hr/lb	52.6	103	237	719	1,100	69.1	134	303	872	1,262

[a]Basis: O:115 lb H_2/kw-h (60% overall efficiency). Average speed: 40 mph.

If we define, as a mission duration, the total integral time of use of the vehicle between refuelings and assume a mixed road average speed of 40 mph, then a 200-mile-range vehicle corresponds to a mission duration of 5 hours calling for a total energy storage of 100 kilowatt-hours, and the resulting total system weight leads to an overall energy density for this particular 5-hour mission of only 52.6 watt-hours per pound. When we consider future long-term technology and a possible cell weight of only 1,410 pounds, only an energy density of 69.1 pounds results. Extending the mission to 10 hours over a vehicle mileage range of 400 miles gives us corresponding energy density ratios of 103 and 134 watt-hours per pound, respectively. The fundamental problem can be even better seen by the presentation shown in Figure 1, which shows that the realization of high energy densities by a fuel cell system does not occur until mission durations well in excess of 10 hours occur, and that, even with future technology, inadequate energy densities are obtained in the primary region of interest. Thus, the fundamental difficulty with all fuel cell systems is that in the case of an electric vehicle in the least favorable range of mission duration it compares unfavorably even with conventional batteries.

There are a number of other comments one can make about fuel cells. For instance, a hydrogen fuel cell would raise, no doubt, serious objections from a safety point of view. Furthermore, the cryogenic storage problems or high-pressure storage problems associated with hydrogen would represent serious technical and distribution difficulties. The hydrazine fuel cell, however attractive because of the storage nature of the anodic reactant, is not considered feasible for economic reasons. The hydrocarbon fuel with its inherent stability difficulties and requirements of costly catalysts also appears far from a practical realization. However, as pointed out previously, the fundamental difficulties discussed above — namely, that in the region of interest for an electric vehicle regardless of its fuel type, low energy densities result — represent a problem common to all fuel cell systems.

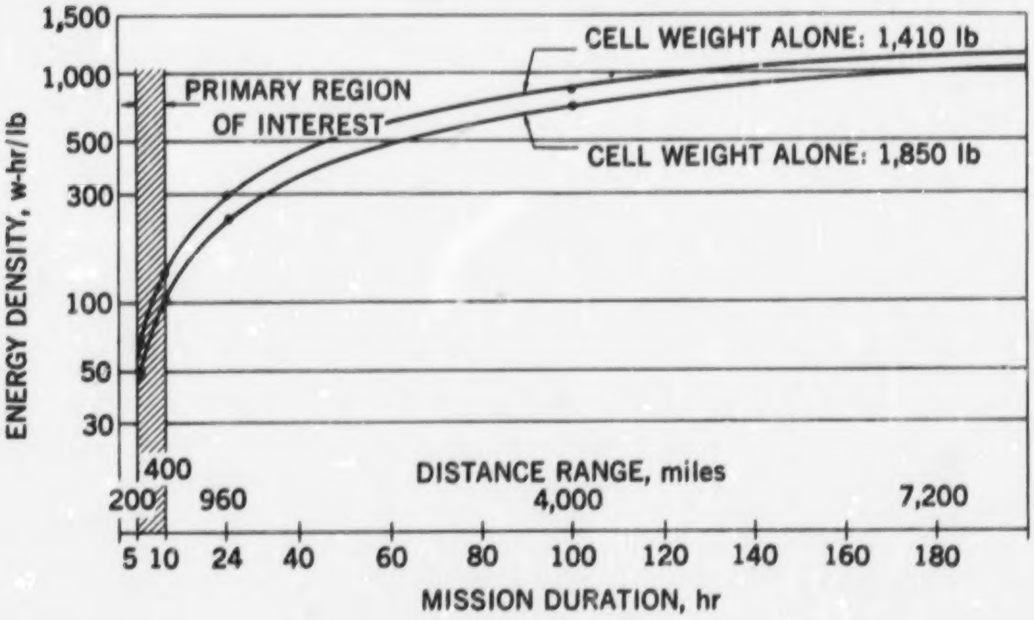

Figure 1. Energy density yields for 20-kw H_2 — air fuel cell as a function of electric vehicle mission duration.

With reference to Table 1 and Figure 1, it should be noted that even the optimistic long-term fuel cell weight of 1,410 pounds represents almost twice the weight allowance that can be made for a compact family car. In other words, even if one would wish to settle for a low-energy-density yield, this would result in the removal of the payload capability of such a vehicle.

ELECTRICALLY REGENERATIVE FUEL CELLS

The fundamental point made above applies also to fuel cells of this type. Furthermore, an additional increase of weight would result from the necessity of providing for a separate loop for handling oxygen in a closed system if this were, for instance, a hydrogen-oxygen rechargeable fuel cell; whereas, in a primary (non-rechargeable) fuel cell, one would simply use air without weight penalty involved. Also, from an electrochemists's point of view, the polarization and consequent energy penalties involved in an electrolysis to a gaseous form are too excessive to make such a system attractive.

METAL-AIR CELLS

These represent a hybrid concept between a fuel cell and a conventional battery. Actually, the concept is old and cells of this type known as "air depolarized cells" have been in use for a long time for railroad signalling. As a result, thin, lightweight, and efficient cathodes for the reduction of air have been developed and it has been possible to design and develop efficient high-energy-density systems. Of all the systems proposed, the alkaline zinc-oxygen, or air system, so far appears to be the most promising. Primary batteries in such a system have been built; they exceed the performance of silver-zinc batteries. However, rechargeable batteries suffer from the same fundamental difficulty that the zinc anode suffers in a silver-zinc battery, namely, short cycle life due to dendritic electrocrystallization of the zinc upon recharging.

A variant of the approach to the metal-air system calls for the use of a primary cell with consumable, replaceable zinc anodes. Under such a concept, solid zinc would be used as a fuel. The engineering complexities of such an approach remain, however, to be worked on; regardless of the approach to the zinc-air system, it must be recognized that there is a considerable weight penalty involved because of the need of providing air cathodes. As a result, despite a high theoretical energy density, when one considers the weight of zinc only, the system is not expected in a rechargeable form to provide energy densities in excess of 80 watt-hours per pound (see discussion below).

AQUEOUS BATTERIES

The well-known limitation of aqueous batteries, as far as energy density is concerned, allows us to reduce the discussion of this class of devices to the silver-zinc battery. With an open circuit voltage of 1.86 volts, this system already represents borderline stability of any galvanic couple in an electrolyte employing water as a solvent. The decomposition potential of water (in these batteries) is somewhere between 1.8 and 2.2 volts. Indeed, a silver-zinc battery cannot be sealed for this very reason, since a spontaneous, however small, generation of hydrogen gas occurs on open-circuit stand. This battery then represents the most energetic system in an aqueous medium with a theoretical energy density of 208 watt-hours per pound, when we consider the weight of active materials only. The highest energy densities achieved for primary cells in this system range between 90 and 105 watt-hours per pound. For secondary cells, energies as high as 55 watt-hours per pound have been achieved. Thus, a rechargeable silver-zinc battery can hardly be expected to provide the energy density required for a vehicle with a practical distance range, and indeed, all designs for vehicles with such batteries point toward a distance range of the order of 40 to 60 miles.

FUSED SALT BATTERY SYSTEMS

The achievement of higher energy densities can, of course, be considered in electrolyte media that are water-free. Such would then permit the resorting to alkali metals in which the combination of high electromotive force forms and low equivalent weight is advantageous. Table 2 shows an interesting tabulation of the individual weight contributions (i.e., a form of a negative merit figure) for certain metals as anode materials. As can be seen, lithium appears the most attractive, and surprisingly, some metals like calcium are more advantageous than sodium. Lithium is approximately 17 times more advantageous than zinc. On the basis of such elementary considerations, the attractiveness of a lithium battery needs hardly any emphasis.

Table 2. INDIVIDUAL WEIGHT-TO-ENERGY AND VOLUME-TO-ENERGY MERIT FIGURES FOR SELECTED ANODE MATERIALS

Material	g/cm^3	Density/ amp-hr	in.^{3}/amp-hr	Half-cell[a] potential ($E°$), v	W_a,[b] lb/w-hr	S_a,[c] in^3/w-hr
Lithium	0.53	5.70×10^{-4}	0.0298	3.02	1.89×10^{-4}	9.86×10^{-3}
Beryllium	1.82	3.70×10^{-4}	0.0056	1.70	2.175×10^{-4}	3.29×10^{-3}
Magnesium	1.7	10.0×10^{-4}	0.0163	2.34	4.27×10^{-4}	6.96×10^{-3}
Aluminum	2.7	7.40×10^{-4}	0.0076	1.67	4.43×10^{-4}	4.55×10^{-3}
Calcium	1.5	16.4×10^{-4}	0.0303	2.87	5.71×10^{-4}	10.5×10^{-3}
Sodium	1.0	19.0×10^{-4}	0.0526	2.71	7.01×10^{-4}	19.4×10^{-3}
Strontium	2.6	36.0×10^{-4}	0.0384	2.89	12.4×10^{-4}	13.3×10^{-3}
Zinc	7.14	26.8×10^{-4}	0.0104	0.76	35.3×10^{-4}	13.7×10^{-3}
Cadmium	8.65	46.2×10^{-4}	0.0148	0.402	111.5×10^{-4}	36.8×10^{-3}

[a] For simplicity of comparison, the standard potential values in aqueous systems, in reference to the standard hydrogen electrode, are taken.

[b] As an individual electrode contribution, W_a is defined as:

$$W_a = \frac{\text{lb}}{\text{amp-hr} \times E°}$$

[c] As an individual electrode contribution, S_a is defined as:

$$S_a = \frac{\text{in.}^3}{\text{amp-hr} \times E°}$$

Fused salt systems can be used for alkali materials, and such systems as lithium-chlorine and sodium-sulphur at temperatures in excess of 1,000°F are being worked on. Although these efforts are essentially in a preliminary laboratory stage, some judgment can be made as to the ultimate value. Molten sodium reacts violently with molten sulphur. Since no ceramic diaphragm that would be used between the two can be expected to be completely failure-proof, a very serious hazard of a violent explosive reaction would exist. This would raise serious objection toward incorporation of such a system in a vehicle. In addition, all molten salt systems are handicapped by very serious materials of corrosion problems. Last, but not least, is the problem of startup time that would be required for a vehicle of this type. A startup time in excess of 5 minutes would hardly be acceptable to the general public. At the same time, it is difficult to foresee how a fused salt system could ever be expected to offer a startup time to full power in less than 30 minutes. Thus, the possible high-energy-density advantages of these systems would be seriously overshadowed by the problems discussed above.

THE NON-AQUEOUS ORGANIC ELECTROLYTE BATTERY SYSTEM

If it is recognized that lithium is a most desirable anode material in a battery and if one wants to build a battery at room temperature, the use of a non-aqueous solvent with a broad liquidity range is indicated. Before proceeding to discuss energy densities of batteries, it is important to realize that they are a function of rate of discharge and of the cell size expressed in terms of ampere-hour capacity. These relationships are pictured in Figure 2 for both the silver-zinc battery and the non-aqueous battery. It will be noted that the slope is steeper for the non-aqueous battery. Because of the generally lower conductivity of non-aqueous electrolytes, compared with that of the aqueous ones, the very high rates of discharge tend to result in a relatively larger impedance losses for the non-aqueous battery. This explains the steeper slope for the plot against the rate of discharge. At the same time, it takes the packaging efficiency of larger cells for the weight advantages of lithium as an anode material to come to the fore. This again explains the steeper slope in Figure 2. It is therefore important in the discussion of any type of a battery to define the conditions at which the watt-hour-per-pound figures are given. This explains why rather broad ranges are given for the operational, practical energy densities in Table 3 for a series of aqueous and non-aqueous batteries. It will be noted, however, that the non-aqueous batteries based on lithium offer very substantially larger theoretical energy densities.

Of the non-aqueous systems, from which so far reasonably successful results have been obtained for a secondary battery, the lithium-silver chloride, the lithium-copper chloride, and the lithium-nickel fluoride systems should be mentioned. The rechargeability

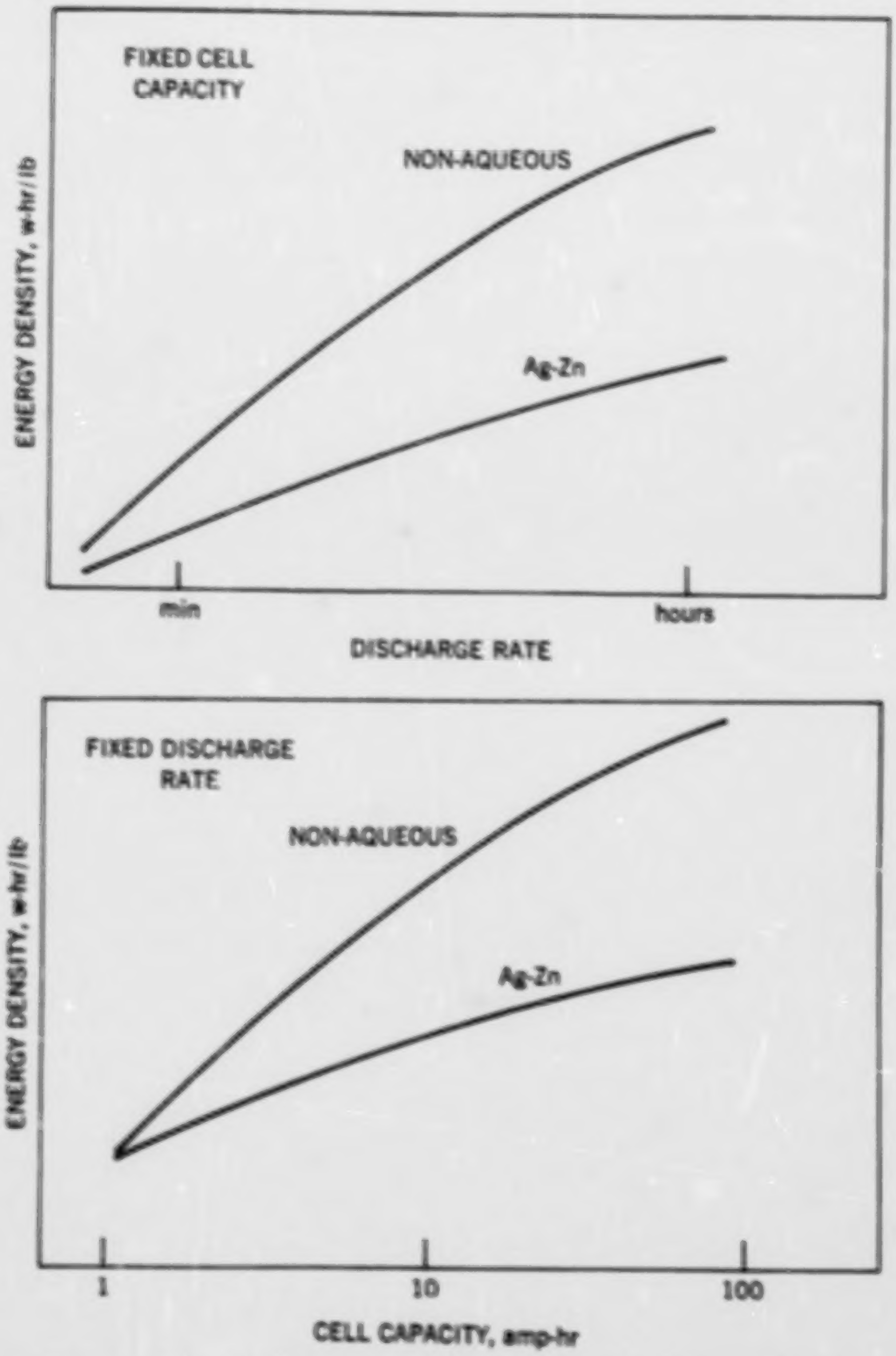

Figure 2. Relationship between (top) energy density and discharge rate and between (below) energy density and cell capacity.

characteristics of these systems have been investigated; indications of favorable performance have already been obtained, even at considerable depths of discharge. Figure 3 shows a non-aqueous cell, type LN-6, cycled at a charge rate of 15 hours (typical of an overnight charge) and discharged at a mild rate of 30 hours. As can be seen, most charging occurs under 4.0 volts and typical discharge voltages are of the order of 2.5 volts. The performance of another non-aqueous cell, Type LN-7, at a rather high discharge rate of 1 hour is shown in Figure 4. Here, the discharge occurs at an average plateau voltage of the order of 2.1 volts. At a typical average rate of discharge corresponding to 5 hours, an average cell voltage of 2.4 volts with fluctuations of the order of ±0.4 volt, can be assumed on the basis of these initial results. As far as a temperature-range capability is concerned, the broad liquidity range of the non-aqueous electrolyte provides the basis for both low- and high-temperature operation. Indeed, one series of cells has been found to operate satisfactorily over the entire range of —40° to +165°F (Kuppinger and Eisenberg, 1966).

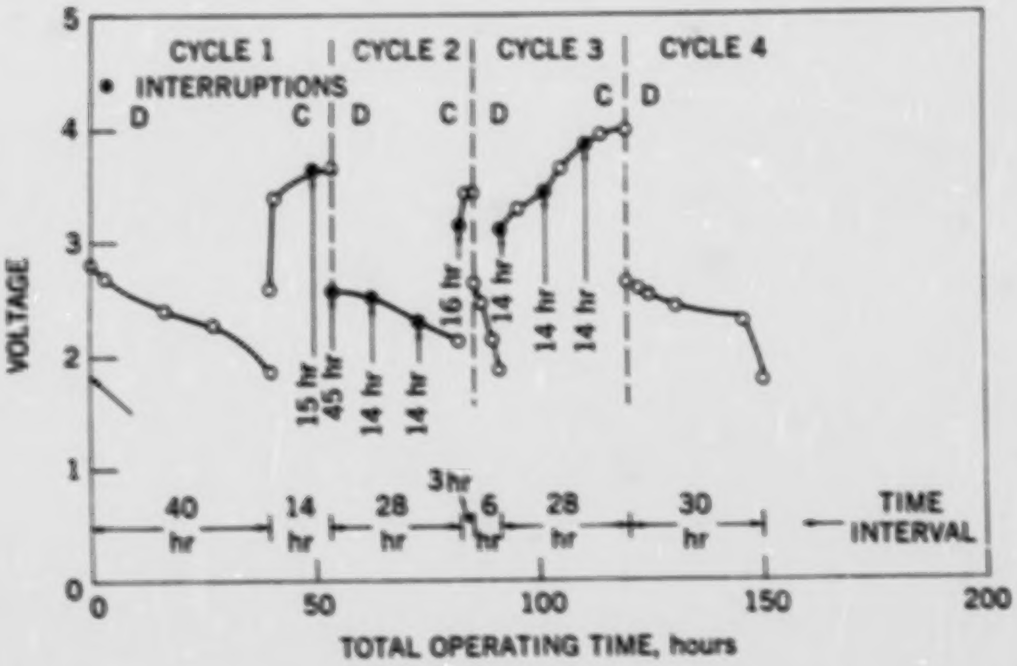

Figure 3. Case history of discharge (d) — charge (c) cycling a type LN-6 cell.

It appears, thus, that non-aqueous battery systems can indeed be constructed, and performance exceeding that of the silver-zinc battery, the highest-energy-density aqueous type, can be obtained. This is illustrated in Table 4, where a general comparison is made between aqueous batteries, metal-air cells, and non-aqueous systems. A distinction is made in the table between primary and rechargeable secondary systems, which generally yield lower energy density ratios

Table 3. SECONDARY BATTERIES

	Aqueous batteries					Non-aqueous batteries		
Types	Lead-acid	Nickel-iron	Nickel-cadmium	Silver-zinc	Silver-cadmium	Li/copper chloride	Li/copper fluoride	Li/silver chloride
Energy density:								
Theoretical on active material, w-hr/lb	115	138	107	208	120	503	746	230
Operational, w-hr/lb	5 to 15	7 to 10	12 to 15	25 to 50	16 to 25	(25 to 175)	(25 to 200)	(25 to 90)
Operational, w-hr/in.³	0.4 to 1.0	0.7 to 1.0	0.7 to 1.0	1.7 to 3.5	1.4 to 2.9	—	—	—
Operating voltage per cell (mid-point)	1.7 to 1.95	1.2	1.1 to 1.23	1.3 to 1.5	1.0 to 1.10	2.3 to 2.8	2.3 to 2.8	2.3 to 2.8
Cycles	200 to 500	2,000+	300 to 3,000	10 to 200	300 to 1,500	—	—	50 to 200 (Exper.)
Operating temperature range, °F	−40 to +140	−10 to +115	−40 to +140	0 to +140	−10 to +140	−40 to +165±	—	—

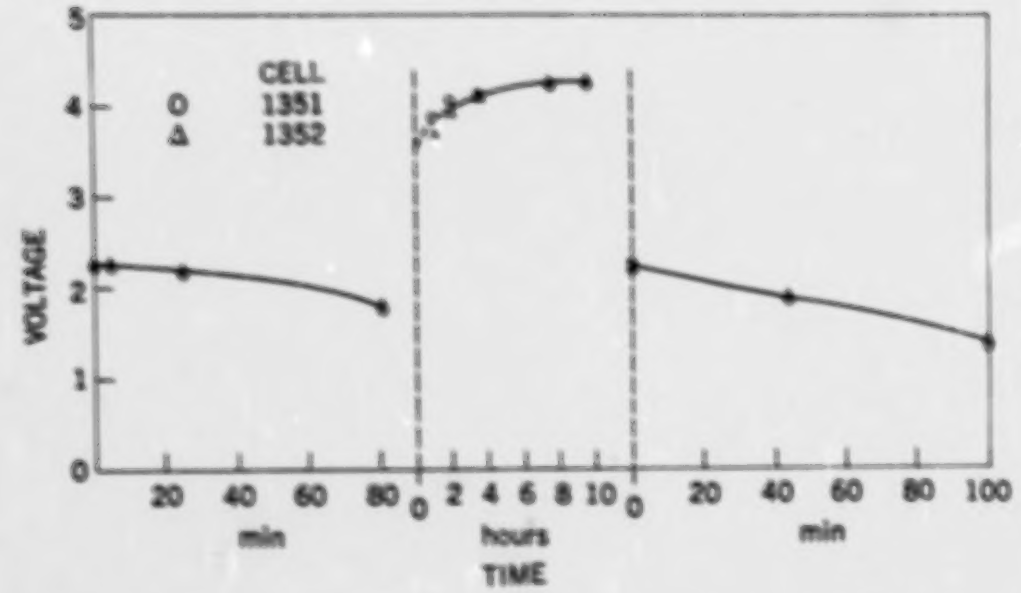

Figure 4. High-rate operation of cell type LN-7 — discharge rate, 1 hr; charge rate, 12 hr.

Table 4. ENERGY DENSITIES OF ELECTROCHEMICAL BATTERY SYSTEMS[a]
(in w-hr/lb)

System	Theoretical	Practical range[b]
Pb-acid (sec)	115	7 to 12
Nickel-Cd (sec)	107	8 to 17
Silver-Cd (sec)	120	12 to 45
Silver-zinc (prim)	208	20 to 100
Silver-zinc (sec)	208	15 to 55
Metal-air cells		
Zinc-air (prim)	671[c]	30 to (140)
Zinc-air (sec)	671	30 to (80)
Non-aqueous high energy		
$CuCl_2$-Li (prim)	503	28 to (230)
$CuCl_2$-Li (sec)	503	20 to (160)
CuF_2-Li	750	?

[a] Specific comparison: 10-amp-hr cells; 10-hr rate of discharge

Silver-Zn:	38 to 43 w-hr/lb	2.4 to 2.7 w-hr/in.^{3}
Non-aqueous (ELCA Type LN-3):	75 to 82 w-hr/lb	4.3 to 4.8 w-hr/in.^{3}
% Increase of energy densities:	78	90

[b] Practical energy yield is a function of rate, size, and construction type.

[c] Considering the weight of zinc only.

because of electrochemical design and mechanical design considerations. Thus, a non-aqueous cupric chloride-lithium rechargeable battery, with a cell capacity in excess of 500 ampere-hours, is estimated to yield 160 watt-hours per pound per cycle compared to 55 for the silver-zinc battery.

The lower portion of Table 4 shows a specific comparison between primary cells, comparing a non-aqueous cell, Type LN-3, to a silver-zinc cell of the same capacity, discharged at the same rate. As can be seen, an average improvement of 90 percent in energy density per unit weight and 78 percent in energy density per unit volume, has been achieved.

The importance of the effect of cell size (capacity) upon both gravimetric and volumetric energy densities can be seen from the experimental data given in Figure 5. Indeed, these results provide the first corroboration of the qualitative figures shown in Figure 2. Going from a 1-ampere-hour to a 10-ampere-hour cell improves the watt-hour per pound ratio for silver-zinc batteries about 25 percent. The improvement is well over 100 percent for the non-aqueous cupric chloride-lithium battery.

Similarly, as shown in the data of Figure 6, a change in the rate of discharge has a much more pronounced effect on the energy density of a non-aqueous cell. In the operation of an electric vehicle the 5- to 10-hour rate of discharge would be more typical than a 20-hour rate of discharge.

Engineering computations for the non-aqueous cupric chloride-lithium rechargeable battery indicate that a 700-pound battery could be built with a base power level of 20 kilowatts and overload capabilities (for acceleration) of 100 kilowatts, i.e. a rate of 5. When the overload is applied, the 1-hour discharge ratio would correspond to the average 5-hour discharge rate. The battery would then have an average power density of 28 watts per pound and an overload power density of 142 watts per pound. If required, still higher power densities are possible as a result of recent improvements in current density capabilities of the system. With a storage capability of 100 kilowatt-hours, the corresponding energy density yield would be 142 watt-hours per pound per cycle. This would correspond to a 75 percent depth of discharge. On this basis, the lithium battery at least offers the possibilities of achieving the design performance discussed earlier in this paper.

The new lithium high-energy battery is beginning to emerge from the pure research area into the initial hardware development phase. Methods are already being developed for construction of cells and battery hardware that once sealed can be handled in ordinary atmospheric environments and that can have the general appearance of conventional batteries.

Relative to the economic outlook, estimates indicate an eventual lithium metal price of the order of \$2-\$3 per pound (Private communication with American Potash Co.). The costs of other com-

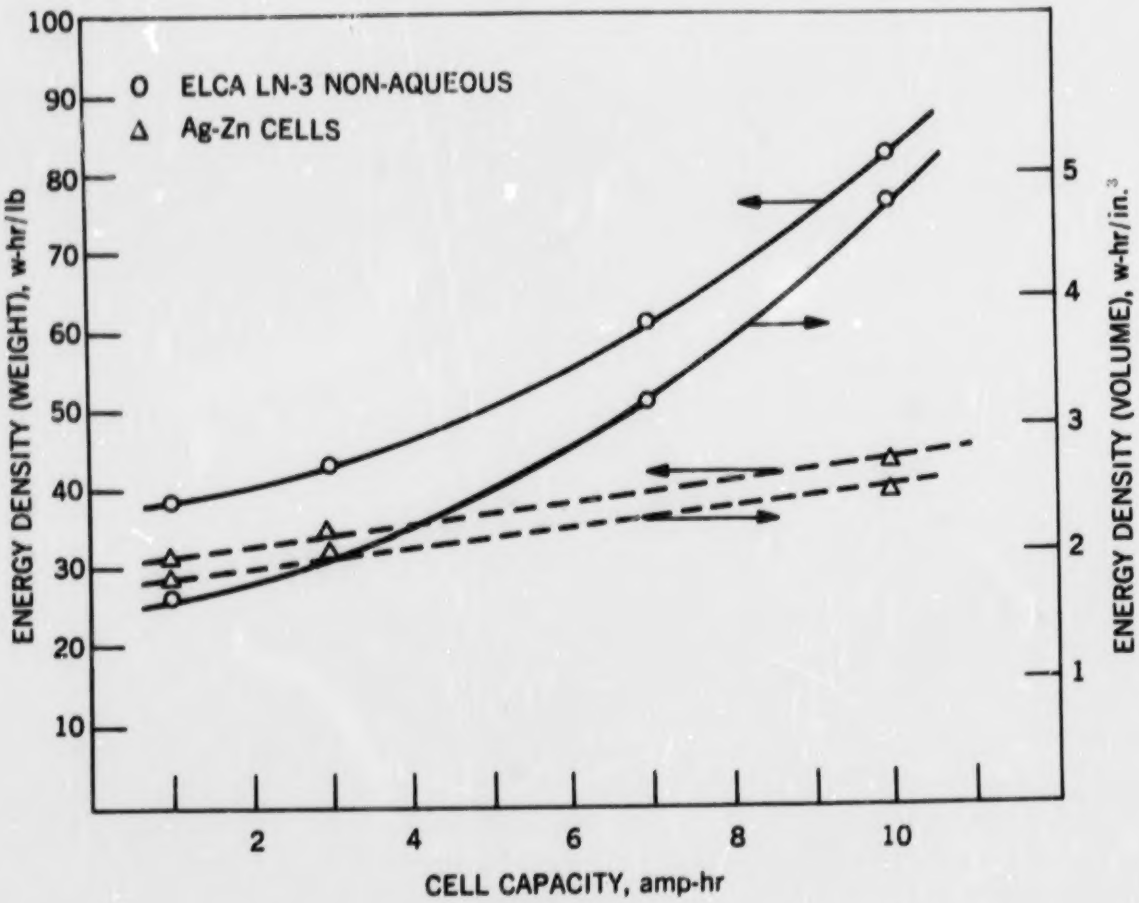

Figure 5. Effect of cell capacity on energy densities — non-aqueous lithium battery and silver-zinc battery.

ponents are essentially in line with present-day conventional batteries. With proper production tooling, the lithium battery is not expected to be unusually costly.

In summary, on the basis of fundamental considerations of energy density, if we eliminate the fused salt, high-temperature system, only the lithium-anode-base organic electrolyte batteries appear to offer an approach toward an energy density of at least 140 watt-hours per pound per cycle, which is considered essential for a practical vehicle with a practical distance range.

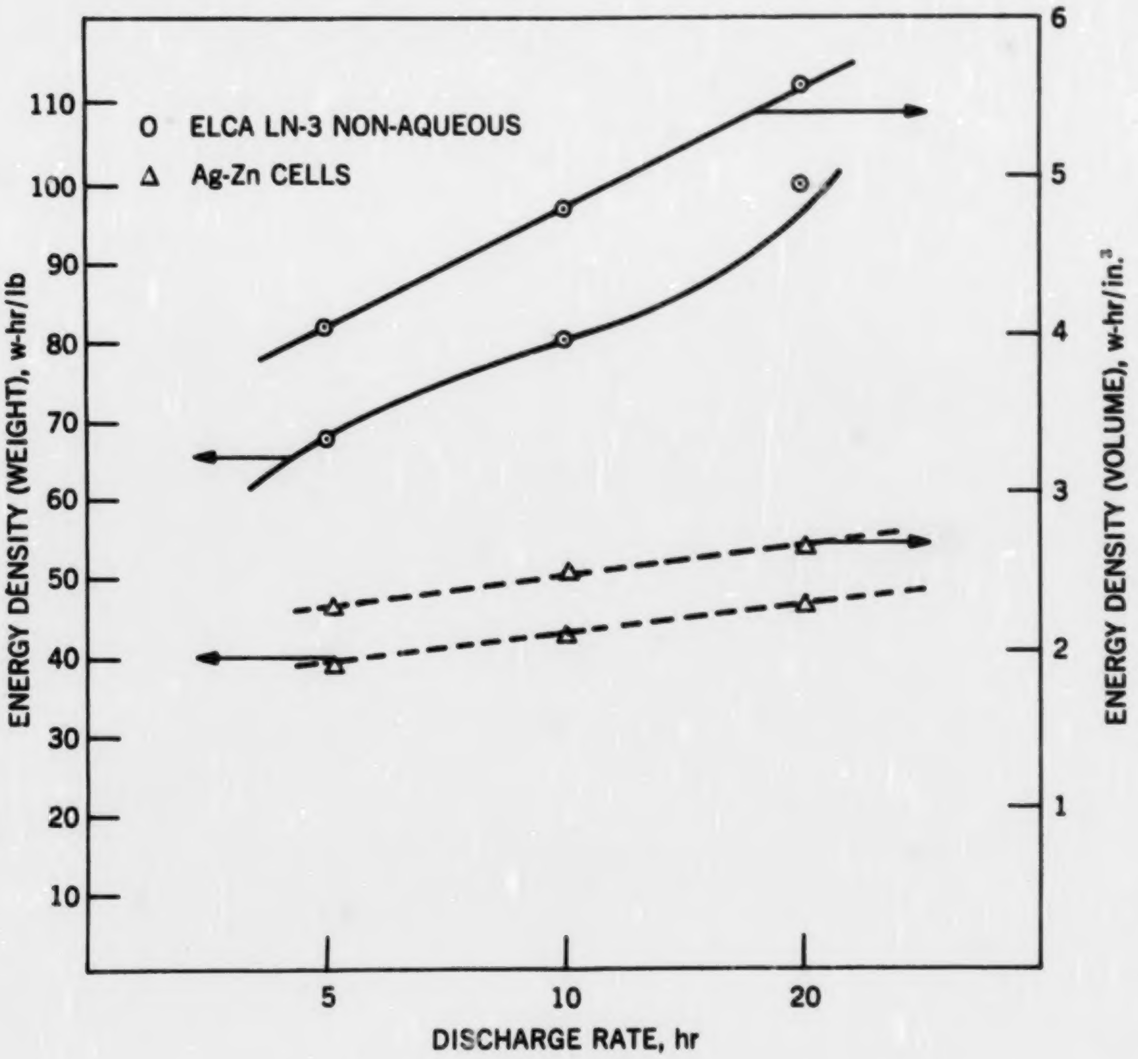

Figure 6. Effect of rate of discharge on energy densities — non-aqueous lithium battery and silver-zinc battery (cell capacity, 10 amp-hr).

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AN ELECTRICALLY RECHARGEABLE ZINC-AIR BATTERY FOR MOTIVE POWER

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The major obstacle in the path of the development of a significant electrically driven vehicle is the excessive weight of presently available electrical energy storage systems. General Atomic, since 1960, has been engaged in a program to develop a secondary battery system with a high energy density for use in vehicles. During the process of selection of an appropriate electrochemical couple, emphasis was placed on the use of low-cost materials, relatively low-temperature operation, and freedom from potential operational hazards for the user. These considerations led to the selection of the zinc-oxygen (air) couple, operating with an aqueous electrolyte at temperatures below the boiling point of water.

Some of the important features of the General Atomic zinc-air battery are as follows:

1. A solid zinc "front surface" electrode is used with the zinc plated on an inert substrate so that substantially all of it can be used during discharge.
2. The electrolyte, an aqueous solution of potassium hydroxide, circulates. This allows the reaction product to be swept from the cell and stored externally.
3. Atmospheric oxygen is introduced as a reactant through a porous nickel "bubbling" electrode.

OPERATION OF BATTERY

During discharge, air from a pressurized air plenum seeps through the porous nickel cathode and bubbles into the electrolyte. A large fraction of the oxygen in the air (assuming that the air supply is compatible with the cell current demand) combines electrochemically with the zinc to form zinc oxide. After some discharge operation, zinc oxide is formed in the electrolyte as a finely divided solid. The waste air with its unused nitrogen is continuously swept from the cell by the circulating electrolyte, as is the excess zinc oxide. The excess zinc oxide is separated from the electrolyte and stored outside the cell.

During charge, essentially a reverse reaction takes place. A potential is applied across the cell while the electrolyte circulates. Zinc from the zinc oxide is replated on the backing sheet, and pure oxygen is evolved at the surface of the porous nickel electrode. The electrolyte continuously dissolves zinc oxide from the storage point outside the cell.

The cells and cell stacks, containing no stored reactants other than the metallic zinc, can be quite compact and relatively light for any given active cell area. The system requires several pieces of equipment in addition to the cell stack, as shown by the schematic diagram in Figure 1. The electrolyte circuit contains a pump to circulate the electrolyte reservoir and an air separator to remove spent air entrained in the cell outlet electrolyte. These items are all arranged close to the cell stack, and the whole assembly is insulated for temperature control. Two other equipment items, which may be located some distance from the cell stack, are the air compressor and the zinc oxide separator and storage container. The zinc oxide separator removes most of the precipitated zinc oxide from the electrolyte and stores it as a relatively dry sludge. Some zinc oxide remains in electrolyte suspension during discharge. Figure 1 also shows a condenser, which cools the air that has been through the cells in order to remove most of the water it has picked up from the electrolyte. The waste heat from this condenser can be used to warm the passenger compartment of the vehicle.

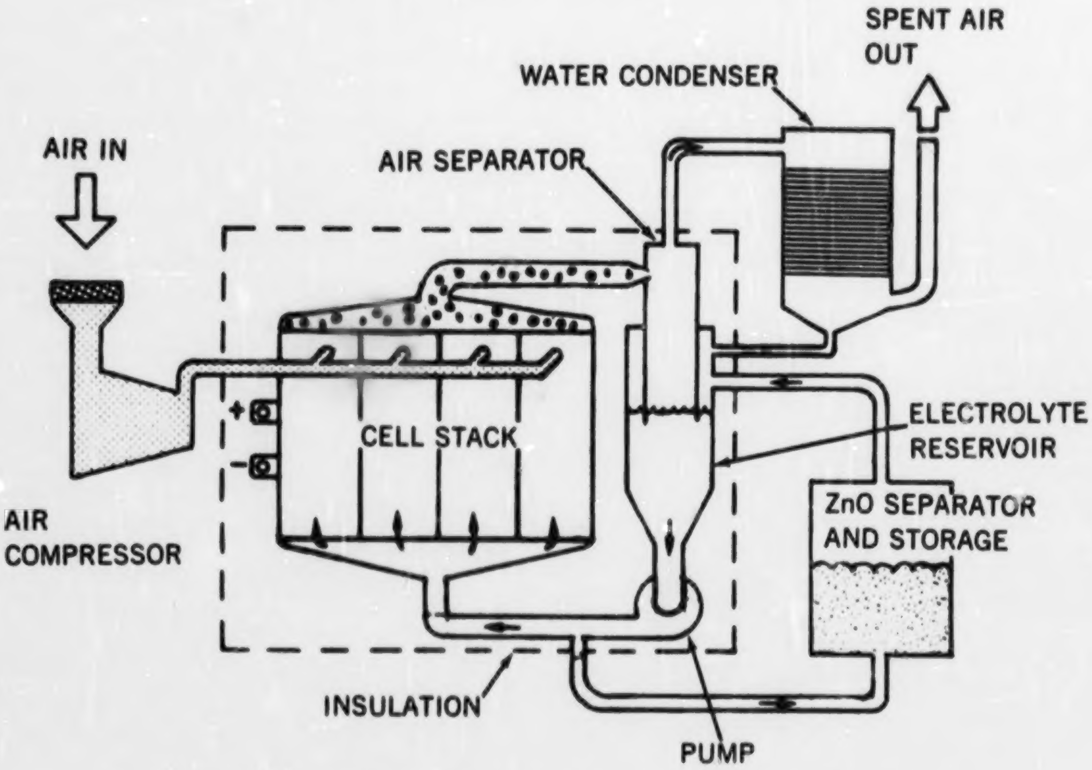

Figure 1. Schematic of zinc-air battery system.

During discharge, voltage varies with the power demand in a manner similar to most battery systems. The voltage variation during discharge time is relatively flat, until nearly full discharge is reached (Figure 2), because of the front-surface operation of the zinc electrode. The zinc that participates in the reaction is taken off the electrode and leaves the cell in the circulating electrolyte. The reaction products, thus, do not impede the reaction. The zinc remaining on the electrode provides the electrical connection to the terminals. The discharge may continue until essentially all of the zinc is removed from the backing sheet.

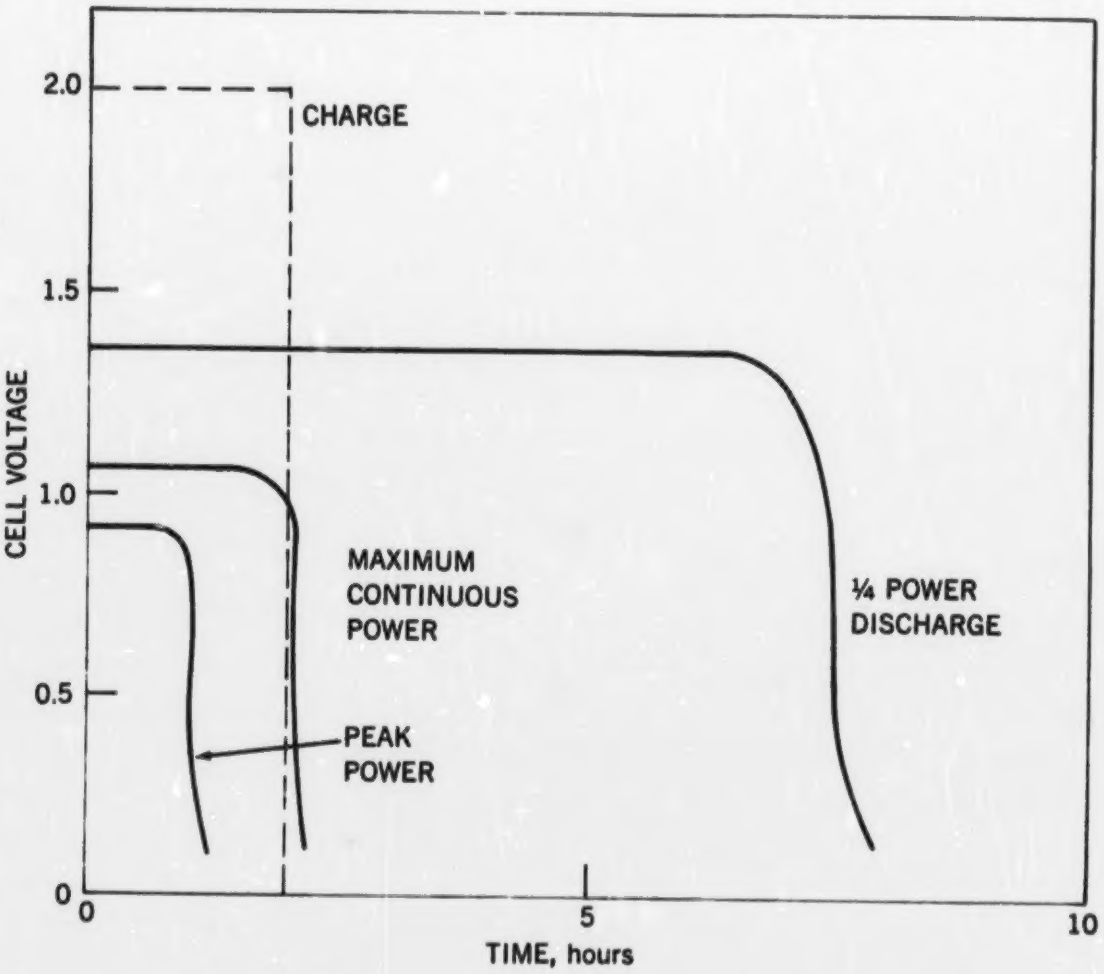

Figure 2. Cell voltage characteristics.

Charging is accomplished at a voltage of about 2 volts per cell. The speed of charging is fast as compared to average discharge times. A cell that would give 8 hours of use in an average lift-truck cycle could be charged in about 2 hours.

HISTORY OF THE PROGRAM

Early experiments (1960-1963) on the air electrodes were performed on small (2 cm^2) electrodes. These experiments were mainly concerned with the performance (polarization) of the electrode as a function of electrode parameters such as porosity, pore size distribution, and thickness. When satisfactory performance of the air electrode had been achieved and the experiments on the plating of zinc from a circulating alkaline solution had demonstrated the feasibility of producing relatively flat zinc electrodes, then a 1-kilowatt-hour "breadboard" battery was assembled (1964). This was followed by the construction of 7- and 14-kilowatt-hour prototypes in 1965 and 1966.

Figure 3 shows present estimates of the achievable energy density plotted against battery size. Because the size and weight of the auxiliaries do not scale linearly with battery capacity, the larger batteries show higher energy densities. The system allows flexibility of design on the question of power versus energy. For example, to obtain higher power levels a given quantity of zinc may be distributed over a greater cell area. This increased cell weight lowers the energy density but raises the power density. Delivery vans, which require higher power densities than transit buses, are shown in Figure 3 at the lower portion of the energy-density band.

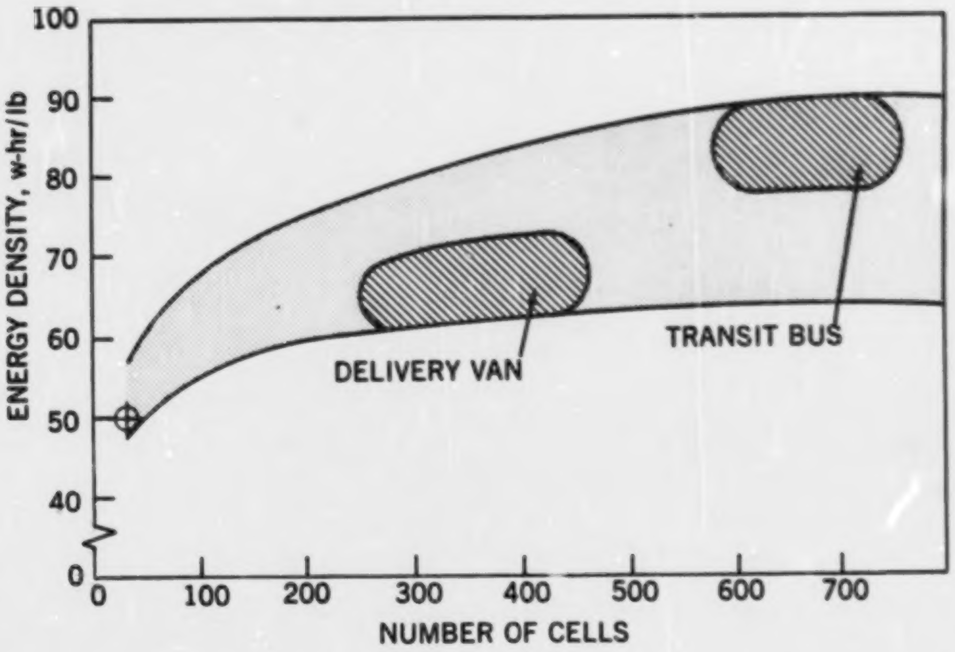

Figure 3. Energy density of zinc-air battery as a function of size.

The amount of space occupied by batteries is also important in vehicular applications. Figure 4 illustrates one possible configuration of the zinc-air battery in a delivery van. The battery system pictured has a capacity of about 100 kilowatt-hours and a maximum rated output of 60 kilowatts. Gross weight of the van is about 5,000 pounds.

The General Atomic program during the next 2 years will be directed at the design, building, and testing of a battery for a delivery van. Capacity will be between 50 and 100 kilowatt-hours. The prototype is scheduled to be ready for bench testing in early 1968 and for preliminary vehicle tests toward the end of 1968.

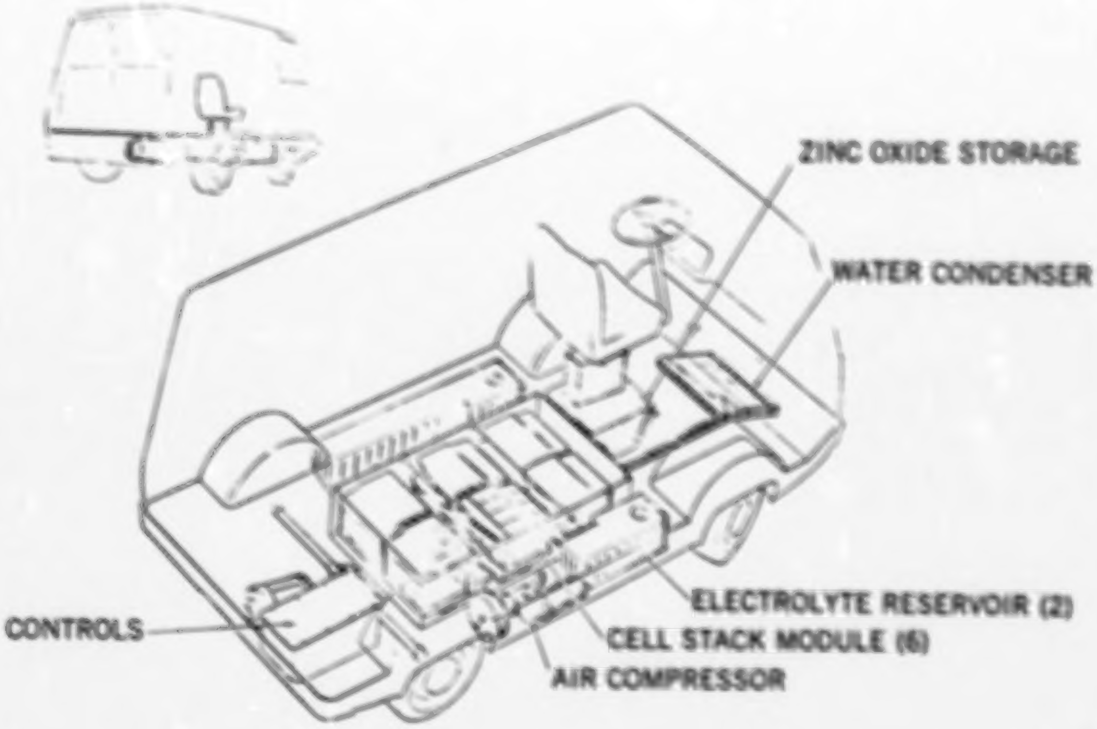
ZINC OXIDE STORAGE
WATER CONDENSER
ELECTROLYTE RESERVOIR (2)
CELL STACK MODULE (6)
AIR COMPRESSOR
CONTROLS

Figure 4. Zinc-air battery system in a delivery van.

ZINC-AIR BATTERIES FOR THE ELECTRIC VEHICLE

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Great Neck, N. Y.

INTRODUCTION

The current renewal of interest in the electric automobile can be attributed largely to two significant developments. The first is the increasing public concern with air pollution and possible means of reducing it. The second development is the recent progress that has been made in energy-storage technology. The prospect of new power sources with higher ratios of energy to weight has permitted the electric car designer to project performance levels approximating those expected by the average driver. The two primary performance requirements for power sources of the electric car are (1) high discharge rate capabilities to satisfy acceleration specifications and (2) high energy capacities to meet operating range requirements. Although energy conversion devices such as fuel cells, in which the source of energy is stored externally, are generally attractive as regards capacity, they are at present excessively bulky and costly. Most available storage batteries, although able to sustain reasonably high drains, have insufficient capacity to give acceptable operating ranges. The purpose of this paper is to review a new type of power source — the zinc-air battery, which promises to meet both the rate and capacity requirements of the electric vehicle.

The zinc-air battery can be regarded as a hybrid fuel cell and storage battery in that half of the over-all electrochemical couple, the zinc, is stored within the battery, while the other half, oxygen, is taken from the surrounding air and electrocatalytically reduced at a non-consumable electrode.

The essential electrode reactions occurring in potassium hydroxide electrolyte are

Zinc Anode: $$Zn + 2(OH)^- \rightarrow ZnO + H_2O + 2\bar{e} \tag{1}$$

Oxygen Cathode: $$\frac{1}{2} O_2 + H_2O + 2\bar{e} \rightarrow 2(OH)^- \tag{2}$$

Over-all Reaction: $$Zn + \frac{1}{2} O_2 - ZnO \quad E - 1.62 \text{ volts} \tag{3}$$

Zinc-air and zinc-oxygen primary batteries have been described (Chodosh, Katsoulis, and Rosansky, 1966[a] and 1966[b]). Briefly, the basic cell consists of a porous zinc anode, impregnated with aqueous potassium hydroxide electrolyte, surrounded by a porous separator, and contained within a structure comprising two hydrophobic air cathodes electrically connected in parallel (Figure 1). A zinc-air cell operating at theoretical voltage (1.62 volts), would have an energy density of 600 watt-hours per pound, based on the weight of zinc only. In practice, this figure is reduced by the weight of non-zinc components, electrochemical irreversibility, etc., to about 150 watt-hours per pound for a primary battery.

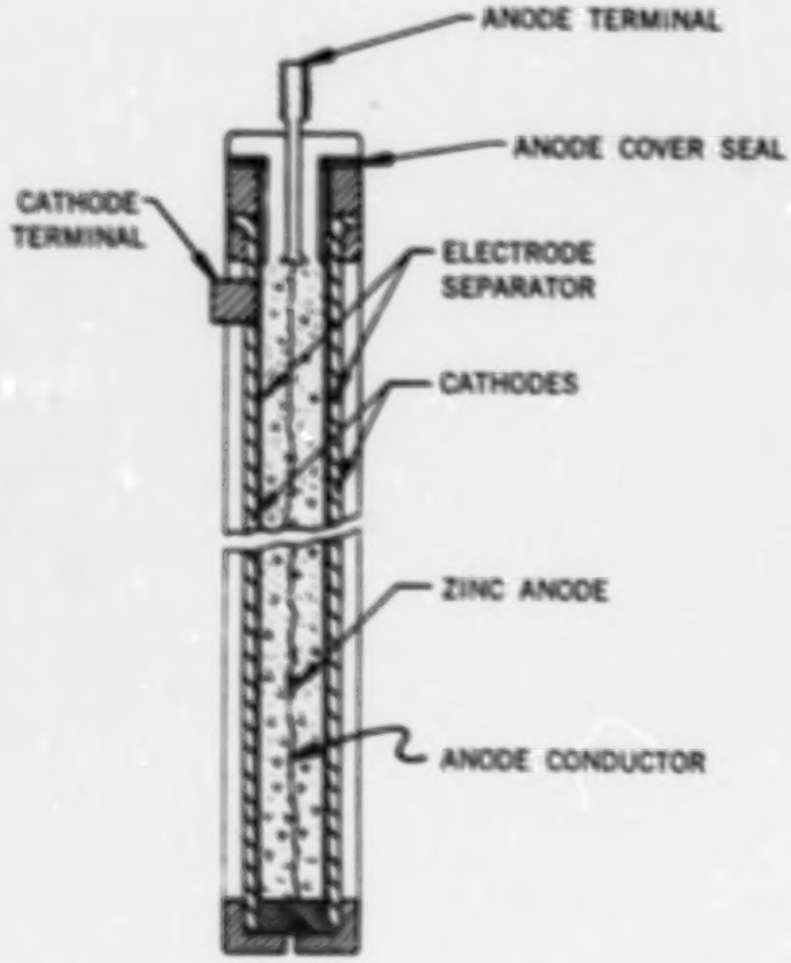
ANODE TERMINAL
ANODE COVER SEAL
CATHODE TERMINAL
ELECTRODE SEPARATOR
CATHODES
ZINC ANODE
ANODE CONDUCTOR

Figure 1. LML zinc-air single cell cross section.

SECONDARY ZINC-AIR BATTERIES

It is axiomatic that a battery intended for use in electric vehicles must have long life and full recharge capability. The approach being followed at Leesona Moos Laboratories in the development of such batteries is to adhere as closely as possible to the basic configuration of the primary zinc-air batteries, incorporating modifications as necessary to achieve the additional capabilities. The purpose of the following brief analysis is to review the major problem areas of the over-all system, their present status, and prospects of solution.

Cycle Life

The principal single requirement that must be added to the capabilities of the primary battery is cycle life. Some of the factors that affect cycle life can be accommodated in a design tradeoff; others require absolute solution. Depth of discharge is probably the most important factor in determining cycle life. Battery research has established that the lower the depth of discharge, the greater the number of cycles obtained. This could be expected, since the ability to store charge depends on the conversion of the zinc oxide produced during discharge back completely to zinc and, more importantly, in a morphological form suitable for the next discharge. Clearly, the greater the proportion of zinc converted to oxide during the previous discharge, the less remains to exert an influence on the morphology of the recharged zinc. At present, 50 percent depth of discharge appears to be about the maximum for good cycle life. Note that this factor of electrode morphology refers only to the consumable electrode. The structure of the air electrode remains unchanged during the cycling.

Discharge Rate

There is evidence that sustained, high discharge rates reduce the capabilities of the zinc-air cell for repeated cycling. As analysis of the urban driving cycle show, however, the sizing of the battery for peak loads on acceleration results in average discharge currents of 25 to 35 milliamperes per square centimeter. This rate is considered relatively low and favors a high cycle life.

Charging Process

Work to date has shown that the charging rate has a profound effect on the cell cycle life. A critical process to be controlled during the charge stage is the production of zinc dendrites. The formation of these crystalline zinc deposits can lead to shorting between the cell plates and result in sudden failure of the battery. One important factor in reducing this hazard is selection of the optimum separator material. New, improved separators, both ceramic and polymeric, offer considerable promise. Charging rate, method of charge, anode thickness, and the quantity of electrolyte are other factors affecting both the growth of zinc dendrites and the life of the zinc anodes. In general, the lower the charging rate, the more complete the recharging process. The critical step in the recharging process is reduction of zincate dissolved in the electrolyte to zinc.

$$Zn(OH)_4^{--} + 2\bar{e} \rightarrow Zn + 4(OH)^- \qquad (4)$$

Work at LML has shown that the crystalline nature of the zinc deposited on charge will vary depending on whether the process is activation or diffusion controlled (Oxley, Fleischmann, and Oswin, 1966). Under activation control (low charge rates), the zinc is deposited in a dense, adherent 'mossy' form, whereas diffusion control (high charge rates) leads to more-crystalline, less-dense zinc deposits giving dendrites. This process in turn depends on the concentration of zincate, and hence on the quantity of electrolyte. In this connection a significant difference between silver-zinc and zinc-air cells may be noted. The latter, having a low-volume air cathode as the positive electrode, contain proportionately less electrolyte. This results in a more activation-controlled process favoring the preferred 'mossy' type of zinc crystalline growth.

In addition to the technical aspects of the charging process, it is important to consider vehicle utilization, which ultimately determines the preferred charging rate. Obviously the ideal battery would be rechargeable in a few minutes, i.e., in the time it takes to refill the gasoline tank of a car. For many military and space applications, such rapid charges are highly desirable; this has dictated the need for charging rates of 10 minutes to 1 hour for some of the studies funded by the government. Although such rates are partially feasible, they do incur a penalty of reduced cycle life. For the electric car application it is clearly reasonable to consider overnight charging (i.e., an 8-hour rate) as the normal situation. This assumption is particularly justified, if the capacity of the battery is sufficient for most daily driving requirements. As the subsequent analysis will show, this appears to be the case of the zinc-air battery.

System Factors

In addition to the battery, a number of system factors must be considered: air flow, heat removal, water control, and contamination by CO_2. Clearly, each of these is affected by the others, so that optimization of the over-all power source requires considerable systems engineering. The thermoneutral voltage corresponding to the enthalpy change for the over-all zinc-air process is approximately 1.80 volts. Operation at voltages lower than this results in evolution of heat. At low rates this heat is advantageous, producing the natural convective flow of air necessary to provide oxygen to the cell. At high rates, however, heat evolution becomes significant and at the same time oxygen demands cannot be satisfied on a continuous basis by natural connection. Under these conditions, forced convection by a blower becomes desirable. A system of this type is shown in Figure 2, a proposed design for a secondary zinc-air battery. The blower imposes small weight and parasitic power penalties on the battery.

During operation, water vapor is transferred into the air stream. Since, unlike operation with fuel cells, no net water is formed by the process, water losses must be made up or prevented. Humidification of the air stream is one option that has been studied. At the highest rates, however, it may be necessary to supplement convective cooling with additional cooling by evaporation. Designs are therefore being considered in which additional water make-up would be provided directly through the anode top. Finally, the problem of carbon dioxide take-up from the air by the alkaline electrolyte must be considered. In practice, primary zinc-air cells have been operated for 400 hours with no deterioration attributable to CO_2 uptake.

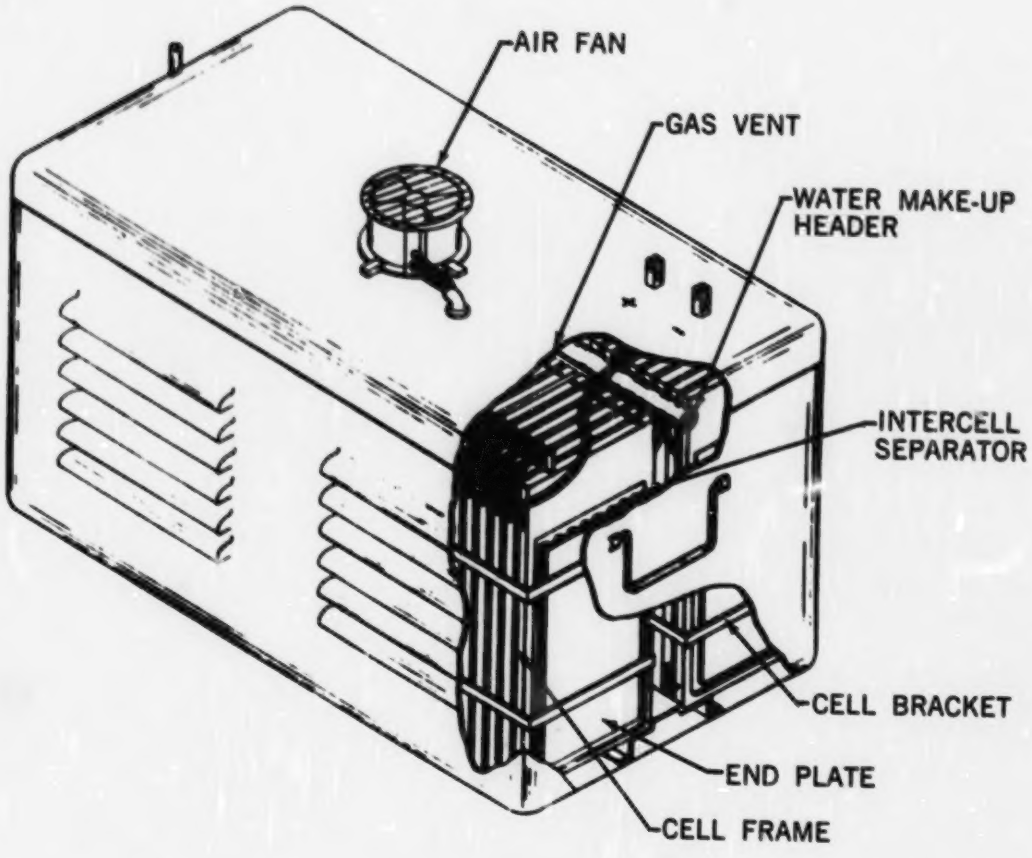

Figure 2. A 120-volt zinc-air battery — 10-kw-h capacity.

Nevertheless, for truly long-term operation in an electric car, some form of CO_2 removal may be required. Soda-lime scrubbers of the type used in fuel cells are being studied for this function. Periodic electrolyte replacement is an alternative solution that will be considered.

DESIGN OF BATTERIES FOR THE ELECTRIC CAR

In sizing a battery for an electric car, one method could be to analyse the maximum power and energy requirements of existing passenger vehicles and translate these directly to battery dimensions. Such an approach is considered unrealistic, however, not only in terms of available battery performance but also in terms of the use patterns for which the electric car is specifically designed. Since the pressures generated within the urban areas have created the requirement for the electric car, it is clearly appropriate to base design of the car and the power plant on urban driving patterns. As regards the car itself, recent studies have shown how reductions in over-all vehicle weight, improved vehicle design, and optimum tire selection can significantly reduce the energy requirements for road and drag losses (SAE, 1967). The present design study envisions a small commuter-type vehicle with a gross weight including passengers of 2,000 pounds.

In determining power and energy requirements, the California City-Driving Cycle was used as the basis for design. This typical urban cycle, widely applied in air pollution studies, defines the percentage of driving spent in the various regimes of acceleration, cruising, deceleration, and idling. A car operating on this cycle would cover approximately 22 miles in 1 hour of driving.

The energy required by an electric vehicle will be that required to overcome road and aerodynamic drag losses during cruising, plus energy expended during acceleration. These represent the energy expended on the wheels. The total energy required from the battery would be higher to account for inefficiencies in the motor, controls, and transmission. An overall efficiency of 78 percent was assumed for these factors. Estimated energy requirements are 2.9 kilowatt-hours per hour of urban driving, increasing to 8.4 kilowatt-hours per hour at 50 mph steady cruising. Maximum power requirements for the urban car will occur during acceleration from 0 to 30 mph. Based on a moderate acceleration performance of 0 to 30 mph in 10 seconds (4.4 ft/sec^2), peak power requirement for the 2,000-pound vehicle is estimated at 20 kilowatts. This requirement would increase to 33 kilowatts if acceleration from 0 to 30 mph in 6 seconds were demanded.

BATTERY SPECIFICATIONS

For the purpose of this analysis a nominal voltage of 100 volts has been assumed. For a point of reference, the requirements are first analyzed in terms of existing primary zinc-air batteries. These, in effect, represent the ultimate limit of performance of the equivalent secondary batteries. For convenience, a standard Leesona battery, the 12-volt, 100-ampere-hour model was selected as the basic design unit. This battery consists of 10 bicells, each with an area of 278 square centimeters. In specifying the battery, the rate limitation will reflect the current-voltage curve of the cell, whereas capacity will be controlled, for a given size cell, by the anode thickness and the utilization of zinc. A voltage-current discharge characteristic of the cell is shown in Figure 3. Although the voltages at the lower current densities are stable under natural convective flow conditions, forced air circulation is required for stable sustained operation at current densities over approximately 70 milliamperes per square centimeter. This is shown in Figure 4, which shows transient load response for current densities up to 250 milliamperes per square centimeter and periods up to 30 seconds. Note that for periods of 1 to 5 seconds voltages may actually be better with natural convection.

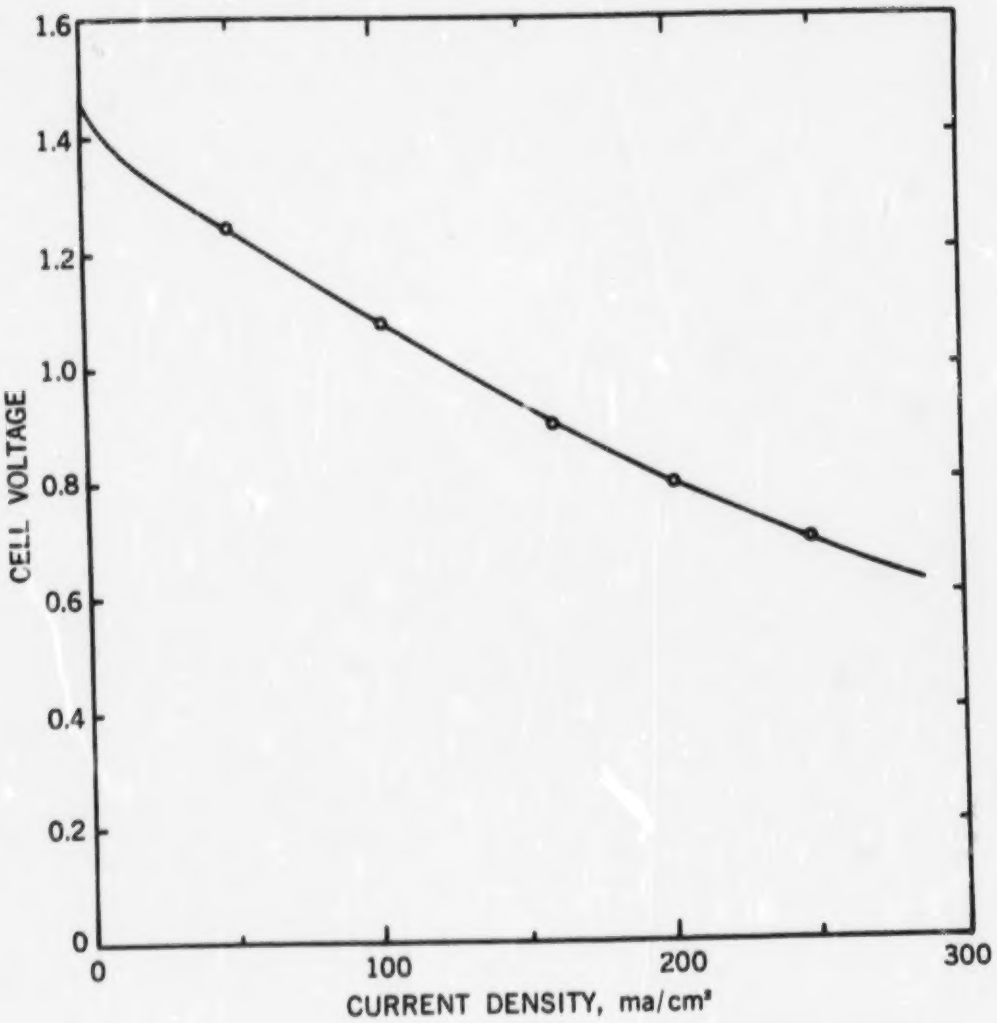

Figure 3. Discharge characteristic of zinc-air battery with blower.

Selecting a current density of 200 milliamperes per square centimeter to correspond to the peak load indicates a requirement of 50 batteries, connected 5 in parallel and 10 in series. These would yield a total capacity of 58 kilowatt-hours, equivalent to about 11 hours of operation on the urban cycle, with an energy density of 150 watt-hours per pound.

In estimating the probable specifications of rechargeable secondary zinc-air batteries, one must consider the factors mentioned earlier. Thus, to obtain satisfactory cycle life, depth of discharge must be reduced and zinc anode porosity increased, both tending to reduce the energy-to-weight ratio. In addition, the systems associated with control of water level, heat removal, and possible CO_2 removal will also contribute to weight and volume. Table 1 shows estimated specifications of batteries for the present electric vehicle application. The first column is based on the performance currently available with Leesona standard primary zinc-air batteries. The second column presents estimates for secondary zinc-air batteries based on current laboratory results. Specifically, the estimates are based on 200-mil anodes, with 80 percent porosity and operation at 50 percent depth of discharge (corresponding to 40 percent zinc utilization). The third column presents some projections based on assumed future technical progress, such as higher zinc-utilization factors, use of thicker anodes, and lighter weight construction for the non-zinc components.

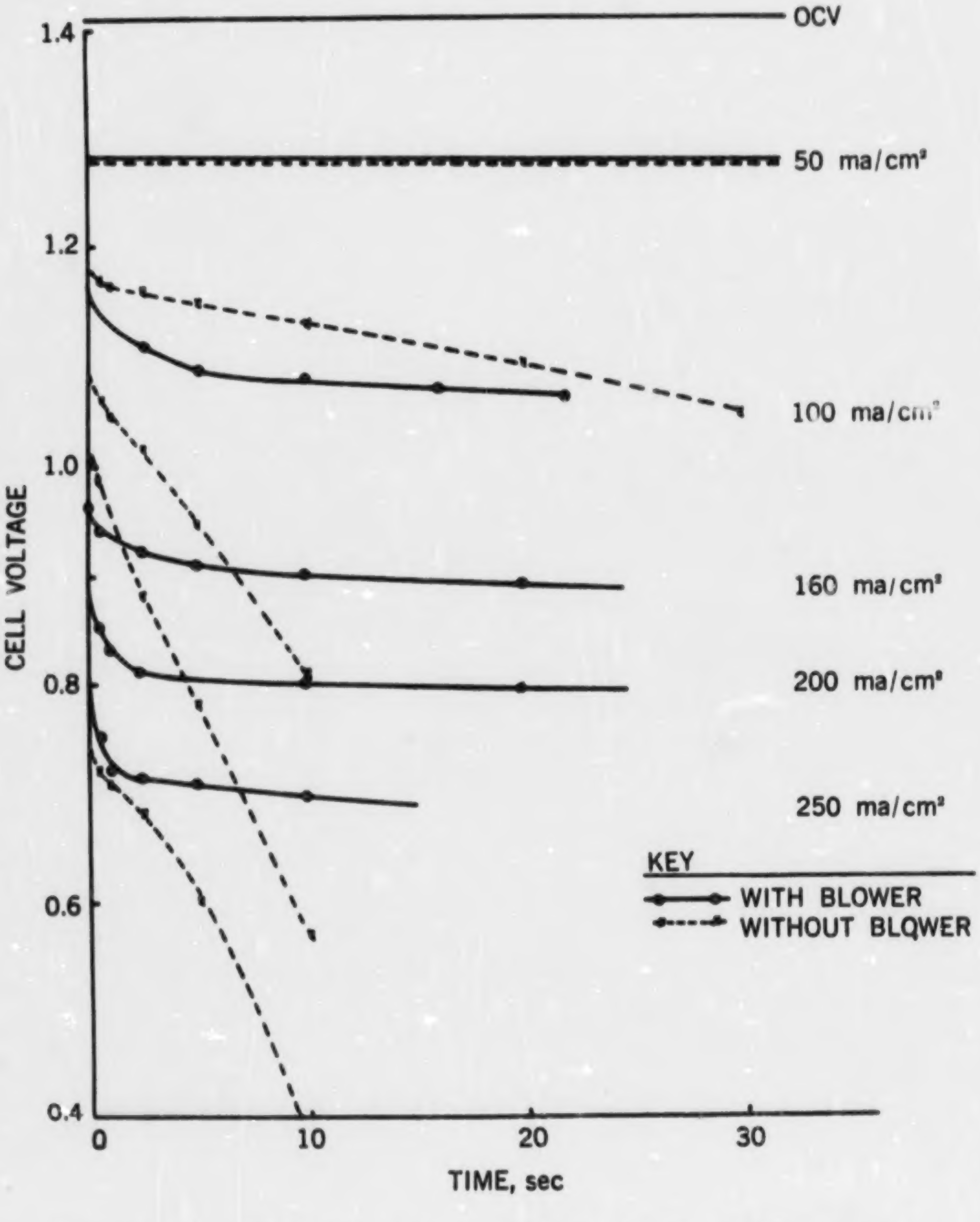

Figure 4. Zinc-air cell transient load performance.

Table 1. BATTERY SPECIFICATIONS FOR 2,000-POUND ELECTRIC VEHICLE

	Present primary batteries	Estimated for rechargeable batteries under development	Longer-term projections for rechargeable batteries
Weight, lb	370	360	350
Volume, ft^3	3.6	4.5	4.0
Capacity, kw-h	54	20	25 to 35
Energy density,			
w-hr/lb	148	55	75 to 100
kw-h/ft^3	15	4.4	6.0 to 8.0
Operation in urban cycle, hr	19	7	9 to 13
Range (at 50 mph), miles	320	120	150 to 220

ALTERNATIVE OPERATING MODES

One of the novel features of the zinc-air battery investigated at LML is the ability to remove and replace the zinc anode after discharge. This is made possible by the non-changing form of the fuel-cell-type air cathode, which in the bicell configuration forms a case within which the anode is contained. This capability in effect gives an extra degree of freedom to the battery designer and offers the possibility of a number of alternative operating modes, shown in Figure 5. These operating modes may also be considered in the context of the electric car. Scheme 1 in a standard throw-away primary cell and is not applicable here.

In Scheme 2, the discharged anode is replaced by a new one at the end of the discharge, the old one being discarded. Batteries of this type are already in limited production for a number of applications. Although such a system would not be economical for the present application, this mode of operation does offer distinct advantages for the immediate testing of prototype electric cars under realistic conditions of battery weight and power.

Scheme 3 is a logical extension of the second. By recharging the discharged anodes externally under controlled conditions in an electrolytic bath, one may circumvent many of the difficulties encountered in an internally recharged true secondary battery. Because of the higher depth of discharge capability, competitive economics might be obtained with this approach. A further operating advantage includes automatic replenishment of water and elimination of CO_2 contamination through equilibration in the charging bath. As with the previous schemes, this system does not seem appropriate for the private automobile, although it might be feasible for an industrial application.

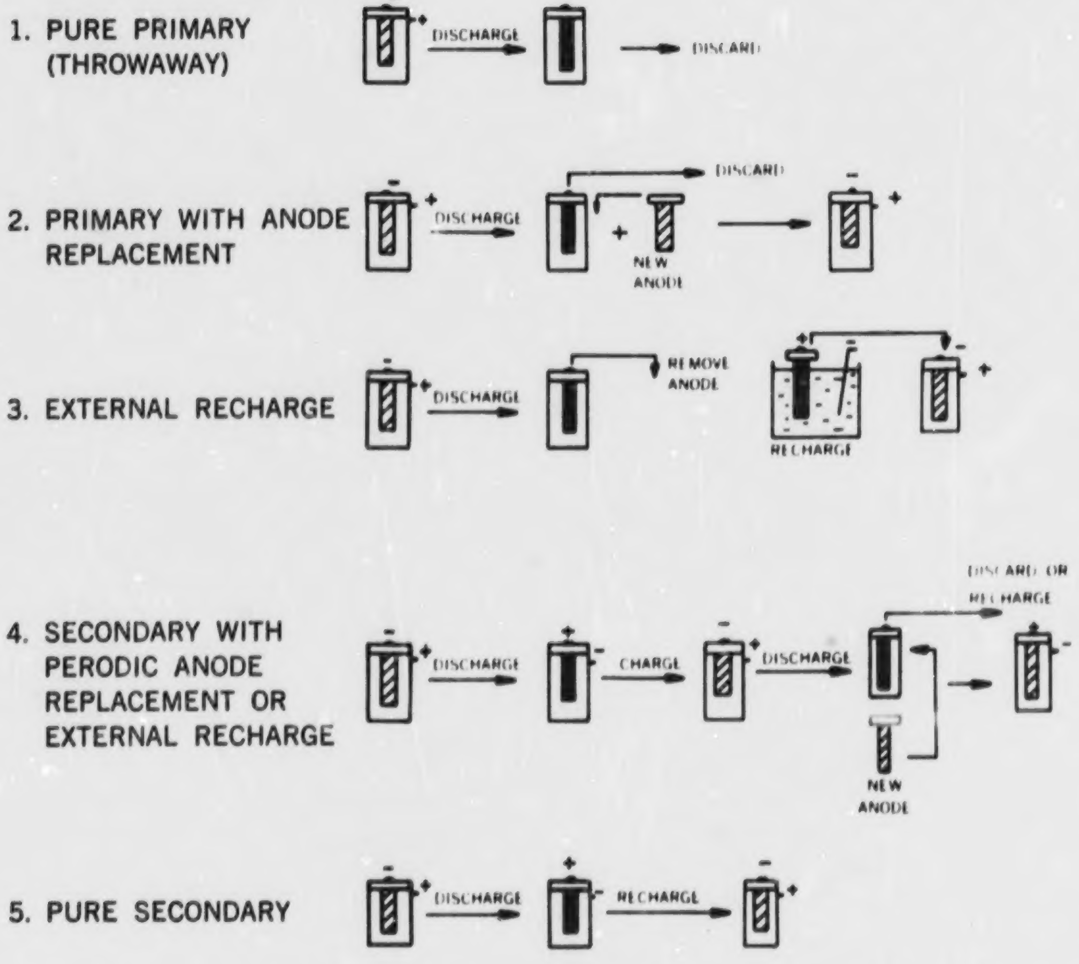
1. PURE PRIMARY (THROWAWAY)
DISCHARGE
DISCARD
2. PRIMARY WITH ANODE REPLACEMENT
DISCHARGE
DISCARD
NEW ANODE
3. EXTERNAL RECHARGE
DISCHARGE
REMOVE ANODE
RECHARGE
4. SECONDARY WITH PERODIC ANODE REPLACEMENT OR EXTERNAL RECHARGE
DISCHARGE
CHARGE
DISCHARGE
DISCARD OR RECHARGE
NEW ANODE
5. PURE SECONDARY
DISCHARGE
RECHARGE

Figure 5. Alternative operating schemes for zinc-air batteries.

Scheme 4 does appear practical and possibiy even optimum for the electric car application. In this scheme, the replacement and/or external recharging technique would be used in conjunction with a true secondary zinc-air capability. The anodes would be replaced or recharged periodically as well as during long trips. The additional capability would offer both operational and performance advantages. Operationally, the replacement could effectively represent a rapid (almost instant) recharge technique. This feature would be important during long-distance traveling; the discharged anodes could be simply replaced at service stations and later recharged for other customers. As regards performance, by accepting a lower cycle life (or life between periodic external charges) one could probably design for higher depths of discharge. Again, as in Scheme 3, the CO_2 problem might be bypassed, although in this case an effective water control system would still be required. Incidentally, the periodic anode replacement could be regarded as equivalent to the regular car maintenance cycles now standard for existing automobiles.

Scheme 5 represents a true long-life, high-capacity, secondary zinc-air battery. Such a battery would only be recharged 'internally' and would have ultra-high cycle life. It may be that if sufficient performance and reliability are obtained, this would represent the ultimate goal for development of a secondary zinc-air battery.

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Oxley, J. E., C. W. Fleischmann, and H. G. Oswin, 1966. Improved zinc electrodes for secondary batteries. Proceedings of 20th Annual Power Sources Conference.

Society of Automotive Engineers, 1967 (Jan. 13). D. M. Tenniswood and H. A. Graetzel. Minimum road load for electric cars, Paper presented at Automotive Engineering Congress (S.A.E.), Detroit, Mich.

Question by Dr. Samuel Ruben: Would enough zinc be available to meet the needs of an electric automobile if the zinc-air battery were to be chosen as the power source?

Answer by Albert R. Cook, Internationl Lead Zinc Research Organization, Inc.: If a 20-kilowatt motor were needed for a small car, the battery would require approximately 250 pounds of zinc. The zinc used would eventually be reclaimed so that the demand for zinc would be expected to build up gradually with electric vehicle production and then level off.

Approximately nine million new automobiles are registered each year in the United States. In the event that electric automobiles were produced at the rate of one million per year, it would be necessary to produce annually an additional 125,000 tons of zinc. I would not expect this to disturb the present market on account of the number of new mines coming into full economical production. World mine output of zinc is expected to increase by over 400.000 tons in 1967, compared with an increase of 206,000 tons in 1965. The consumption of zinc in the United States during 1966 was 1,400,000 tons at a stable price of 14½ cents per pound. It would be necessary to watch the capacity available for the production of 99.99 per cent pure zinc, since this may be required. Fortunately, such high-purity zinc is traditionally available commercially, and no difficulty is anticipated.

Comments have been made concerning the energy density of the lead-acid battery. It should be appreciated that the starting, lighting, and ignition battery used in automobiles is most efficiently designed for its purpose. It can achieve approximately 17 watt-hours per pound. It is designed for operation under float conditions with occasional heavy current drain and is not, therefore, suitable for deep cycling. The industrial battery can typically provide up to 12 watt-hours per pound and successfully withstands deep cycling for long periods. Given an incentive such as is now provided by the prospect of a battery- or hybrid-powered automobile, it should be possible to plan on the near-term achievement of 20 watt-hours per pound for a lead-acid battery of optimum life. The International Lead Zinc Research Organization, Inc., has just commenced a 6-month study to define the contribution the lead-acid battery can make to the development of the electric vehicle and to identify the characteristics that should be designed into the optimum power source. The results of this study will be available to anyone interested.

PROBLEMS RELATED TO HIGH-ENERGY BATTERIES

Samuel Ruben

Reuben Laboratories

When current flows in any electrochemical system, electrode reactants are consumed and end products are formed. If the products are soluble, they change the characteristics or the conductivity of the electrolyte, particularly the temperature coefficients, until saturation is reached, and then accumulation on the electrode surface such as the anode decreases ionic mobility and ion diffusion. Ions immediately adjacent to the cathode must be discharged in order for current to flow through the circuit, otherwise an ionic gradient is established, which is equivalent to electrode polarization drop. This process is very temperature sensitive, depending upon the depth of the ionic gradient, the transport number of the ions in solution, and the concentration of the diffusing ions in mols per liter. To obtain the minimum electrode polarization drop of potential and the necessary ion diffusion requires large effective anode areas and relatively close spacing. This would necessitate the use of a porous zinc amalgam electrode and a residual anode structure that could maintain its porosity during recharge cycles.

One important factor that must be considered with zinc alkaline cells is that as soon as a current is discharged ionization of the zinc occurs ($Zn - 2e \rightarrow Zn^{2+}$), with the formation of zinc hydroxide, which dissolves into the alkaline electrolyte, forming zincates. When the electrolyte is saturated with zincate, the anode reaction product is then deposited on the anode as a white pasty mass that consists essentially of zinc oxide ($Zn(OH)_2 \rightleftharpoons ZnO + H_2O$). This layer of zinc oxide, if thick enough, is gravity sensitive and can, under vibration, fall off and deposit at the lower end of the electrode. The important variation is not so much the mechanical effects, but the change in the temperature coefficients of the system, as it affects the IR and electrode polarization drop. With a new cell it is possible to operate at low temperatures without excessive voltage drop or polarization, but as soon as the alkaline electrolyte becomes zincated, the cell requires higher temperatures and the output drops off very rapidly with the lowering of ambient temperature. This temperature coefficient imposes a problem with an electric car, where atmospheric changes in temperature can be wide enough to reduce the cell or battery output to an inadequate value.

One specific problem in zinc alkaline cells is the spacer, which must allow ionic conduction with a low voltage gradient, particularly at lower operating temperature, yet prevent any migration of electrode composition or reaction products. Our experience with rechargeable cells is that the major function of the spacer is to maintain as uniform a current distribution over the electrode area as possible. With localized currents of high density, dendritic zinc deposits produced force their way through the spacer, producing bridging paths with internal discharge of the cell. In our work with alkaline cells over the past 25 years, we have found that sintered ceramic spacers, particulary magnesium oxide, are the only ones with which we could obtain repetitive results. Once dendritic growth has been formed on one section of the anode, its mass increases even at low current densities. Placement of the spacer close to the anode surface confines solid anodic products and prevents mechanical change. At the same time, however, it also becomes important to avoid compression of the zinc oxide formed, since a high-density layer rapidly increases the ionic gradient, causing greater electrode polarization drop of potential. If the cathode is soluble or if colloids are formed, the spacer must also have a filter action to prevent its metallization with bridging circuits. Alkaline battery systems utilizing consumable anodes such as zinc are inherently not well adapted to series connection over long cyclic operation. Unless a sustained balance between the coulombic capacities of anode and cathode is maintained, progressive changes in unbalanced cells can take place, with detrimental effects. The problem of series connection could be a factor; if a cell is prematurely exhausted, it would set up a reverse potential. This could happen if the cell had excessive local action or initially insufficient zinc for the proposed current and time of discharge. With air-zinc cells, the carbonation of the electrolyte by the carbon dioxide content in the air could materially affect performance.

Another problem that must be considered for rechargeable air-zinc cells, other than the electric power facilities in the average garage, is the hazard introduced by the generation of oxygen at the cathode during recharging. Oxygen is released at the rate of 0.658 pound per 1,000 ampere-hours. For a 50-kilowatt-hour battery, this would amount to 35 pounds or more of oxygen per charge.

Although other high-energy anode materials look attractive, the major problem is to cope with their high reduction potentials, which make necessary the use of non-aqueous electrolytes. In some instances, inhibitors can make the electrode passive, but as soon as current is discharged through an aqueous electrolyte, the electrode area becomes active to the aqueous component of the electrolyte and hydrogen is displaced, with a loss of anode material.

THE ATOMICS INTERNATIONAL SODIUM-AIR CELL*

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INTRODUCTION

The aim of Atomics International's sodium-air cell project is the development of a compact sodium-air cell operating isothermally at a temperature slightly above the melting point of sodium. Preliminary engineering studies have shown that this system can be developed into a battery system with high energy and power density for application as a power source in automobiles.

The first part of this paper summarizes the general criteria used in the engineering studies that led to the selection of the sodium-air system for experimental development. This is followed by a description of the sodium-air cell, a review of the experimental results, and a discussion of the potential performance of the system.

BATTERY CRITERIA FOR AUTOMOTIVE POWER APPLICATIONS

The technical and economic feasibility of using secondary batteries as power sources in automobiles requires that the battery system satisfy a large variety of criteria. The criteria summarized in Table 1 were used in our study of possible power sources for passenger automobiles. Although we recognize that possibly no system will meet all these criteria, the one best filling these requirements would be most attractive for automotive use. An estimate of energy and power density requirements in various vehicle applications is shown in Table 2.

The requirement of high energy density can be best satisfied by using hydrogen or a light alkali or alkaline earth metal as the anodic reagent together with a strong oxidizing low-molecular-weight cathodic reagent. A consideration of other important criteria (e.g. high power-to-weight ratio, which requires high current density; long cycle life, which requires uniform deposition of the metal on charging) shows that the use of molten alkali metals has several advantages. The rate of electrode reactions at a liquid metal and electrolyte interface is generally very high and therefore high current densities can be achieved. Furthermore, the molten state of the metal assures uniform deposition on charging and thus long cycle life of the metal electrode. The use of molten metals also permits the construction of very compact cells since most of the metal can be stored outside of the cell and supplied continuously to the anode compartment at the required rate. In this sense the system can be regarded as an electrically rechargeable fuel cell as well as a secondary battery.

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*Work performed under company sponsored research program. Patents pending.

Table 1. CRITERIA FOR POWER SOURCES IN ELECTRICAL AUTOMOBILES

Performance criteria[a]
- Energy-to-weight ratio[b] of cell battery: > 150 w-hr/lb
- Power to weight ratio[b] of cell battery, nominal: > 35 w/lb
- Overload capability: greater than 200%
- Energy efficiency (% energy out/energy in): ≥ 50%

Other criteria
- Long shelf life and cycle life
- No severe materials or corrosion problems
- Low production cost
- Durability and reliablity
- Easy startup

[a] For 4 hours of operation at nominal power level. This power level permits continuous operation at a speed of 60 mph on a level road.

[b] Based on total weight of battery and reactants.

Table 2. ENERGY AND POWER DENSITY REQUIREMENTS

Application	Energy density,[a] w-hr/lb	Nominal power density,[a,b] w/lb
Industrial carts, small delivery trucks, other small vehicles	10	2.5
Standard delivery trucks	40	10
Army vehicles	100	25
Automobiles	150	35

[a] For 4 hours of operation at nominal power level.

[b] The battery system should be capable of delivering at least twice the nominal power output for short periods.

Sodium was chosen from the light alkali metals as the most promising anode feed material. It has the advantages of a lower molecular weight than potassium and a lower melting point than lithium. The low melting point is a very important factor because it permits a low operating temperature, and many important requirements (materials compatibility, corrosion resistance, safety, ease of startup) can be best satisfied at low temperatures.

Air was selected as the cathode feed material because it is readily available from the atmosphere and thus need not be stored and carried in the vehicle. This advantage outweighs the drawback of relatively high polarization losses at this electrode.

On the basis of a detailed analysis, the system selected as the most promising for experimental investigation was a sodium-air cell operating somewhat above the melting point of sodium. In principle, the electrochemical reaction of sodium with oxygen from air can be carried out in one step. However, one-step oxidation requires a highly conductive electrolyte that is chemically compatible with both molten sodium and oxygen. Since the development of such an electrolyte presents a formidable problem, a two-step method was chosen for development.

THE ATOMICS INTERNATIONAL SODIUM-AIR CELL

The two-step or dual sodium-air cell system can be characterized as follows:

$$\underbrace{(-)\ \text{Na} \;\Big|\; \begin{matrix}\text{Molten sodium}\\ \text{salt}\end{matrix} \;\Big|\; \text{NaHg}_x}_{\text{Step A}} \underbrace{\;\Big|\; \begin{matrix}\text{Aqueous}\\ \text{NaOH}\end{matrix} \;\Big|\; \text{O}_2\ (\text{air})\ (+)}_{\text{Step B}}$$

The two cell reactions involved are:

$$2\ \text{Na} + 2x\ \text{Hg} = 2\ \text{NaHg}_x \qquad \text{(in Step A)} \qquad (1)$$

and

$$2\ \text{NaHg}_x + \tfrac{1}{2}\text{O}_2 + \text{H}_2\text{O} = 2\ \text{NaOH} + 2x\ \text{Hg} \ \text{(in Step B)}. \qquad (2)$$

The amalgam electrode acts as the cathode of cell A and the anode of of cell B. Sodium is transported across the amalgam electrode by diffusion and convection.

The net cell reaction and the calculated value of the corresponding reversible cell potential at an cperating temperature of 130°C are

$$\begin{aligned}&\text{Na (liq)} + \tfrac{1}{4}\ \text{O}_2\ \text{(air)} + \tfrac{1}{2}\ \text{H}_2\text{O (50 wt \% NaOH)}\\ &\quad = \text{NaOH (50 wt \% NaOH)} \qquad (3)\\ &E = 2.72 \pm 0.03\ \text{volt}\end{aligned}$$

If the amalgam electrode contains 2 atom percent sodium, the calculated reversible cell potentials of the two subcells are as follows:

Na/Na-amalgam (2 a/o Na); $E = 0.83$ volt
Na-amalgam (2 a/o Na)/0_2 (air); $E = 1.89$ volts

A schematic diagram of the cell is shown in Figure 1. The cell consists of a sodium compartment, a molten salt electrolyte matrix, an amalgam electrode, an aqueous NaOH electrolyte compartment, an air electrode, and an air compartment. On discharge sodium is supplied continuously from an outside container to the sodium compartment. Cell reaction (1) takes place in the Na/$NaHg_x$ subcell, and sodium is deposited on the sodium side of the amalgam electrode. Sodium migrates across the thin, stationary amalgam electrode under the effect of a concentration gradient and is made available for cell reaction (2), which takes place in the $NaHg_x/O_2$ (air) subcell, where aqueous NaOH, the product of the overall reaction, is formed. The aqueous NaOH solution is kept in circulation through the cell and the electrolyte storage tank. Its concentration is kept constant by the addition of water at a rate proportional to the rate of NaOH formation.

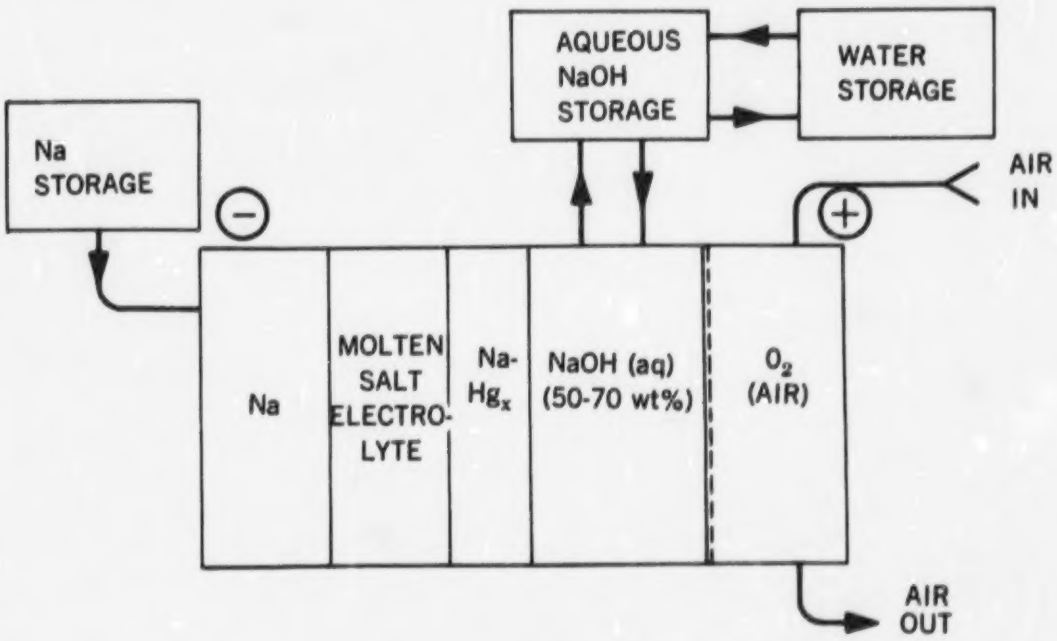

Figure 1. Schematic diagram of sodium-air cell

On recharge, the aqueous NaOH solution is electrolyzed (reverse of reaction (2) in cell B); sodium is deposited on the amalgam electrode; and oxygen evolves on the air electrode. The oxygen is released to the atmosphere. The concentration of the aqueous electrolyte is kept constant by evaporating water at a rate proportional to the rate of NaOH electrolysis. Sodium migrates across the amalgam electrode, and in cell A the reverse of reaction (1) takes place. Sodium is deposited on the sodium electrode and the excess sodium flows back into the sodium storage tank.

Note that these operating features distinguish the Atomics International cell concept from previously proposed designs for a primary sodium-oxygen cell (Eidensohn, 1962) or a secondary potassium air cell (Koch and Karas, 1963), in which the two subcells were operated at widely different temperatures and a circulating amalgam electrode connected the two subcells.

EXPERIMENTAL RESULTS

Component Development

Preliminary engineering studies indicated that a key requirement for developing a high-power-density sodium-air battery is the achievement of current densities in the range of 100 to 200 milliamperes per square centimeter. This current density range — with other major criteria — defined the basic requirements of the cell components and set the goals of the component development program. The component requirements and the results of the first phase of the experimental program are summarized in this section.

Electrolyte for the Sodium/Sodium Amalgam Cell

The principal requirements of the electrolyte are

1. It should have a specific conductance greater than 0.1 mho per centimeter.
2. It should be chemically compatible with sodium and dilute sodium amalgam.
3. It should contain Na^+ as the only cation, and oxidation and reduction at the electrodes should involve only this ionic species.

A molten sodium salt electrolyte of proprietary composition that satisfies these requirements was developed. The freezing point of the electrolyte is 127°C. Its specific conductivity was measured in the temperature range of 130° to 165°C with a conductivity cell made of alumina. Conductivity values in this temperature range fit the following equation:

$$K = 1{,}370 \exp - \frac{6{,}790}{RT}$$

where K is the specific conductance in mho per centimeter. The value of K, calculated from this equation, is 0.28 mho per centimeter at 130°C.

Chemical compatibility of the molten salt electrolyte with the liquid metal electrodes and various cell structural materials has been investigated. No significant degradation of the electrolyte could be detected at temperatures up to 150°C over test periods of several hundred hours.

Amalgam Electrode

The amalgam electrode must form a thin, continuous layer anchored firmly in a stable supporting structure. Design studies have shown that the thickness of the amalgam electrode must be less than 0.3 millimeter (preferably as small as 0.1 mm) to give high energy and power density and low materials cost.

Electrodes with amalgam layer thicknesses in the range of 0.35 to 1.0 millimeter have been tested successfully. At operating temperatures of 130° to 135°C, current densities up to 70 milliampere per square centimeter (on discharge) and 50 milliampere per square centimeter (on charge) were obtained with an amalgam layer about 0.4 millimeter thick.

Air Electrode

Good cell performance and economical operation require durable, low-cost electrodes with polarization (with respect to the theoretical oxygen reduction potential) less than 0.4 volt at current densities greater than 100 millamperes per square centimeter.

Most work performed to date has been concerned with the interim goal of testing commercially available electrodes and adapting them to the operating conditions of the sodium-air cell. We found that the required performance could be obtained with electrodes made with a platinum loading of 10 milligrams per square centimeter, but the lifetime of these electrodes at 130°C in 50 to 70 weight percent NaOH was much less than under normal conditions (25° to 70°C in 6N KOH electrolyte). Flooding of the electrode and solidification of NaOH on the electrode surface were found to contribute significantly to the deterioration of performance. Precise control of the humidity and temperature of the air feed is required to alleviate these difficulties and ensure stable operation. Typical cathodic polarization data obtained with a commercially available electrode (American Cyanamid AB-6) are shown in Table 3.

Table 3. AIR ELECTRODE POLARIZATION DATA

Air feed	Humidified, CO_2 removed; air pressure: 2.5 psig
Catalyst loading	10 mg Pt/cm^2
Electrode surface area	16 cm^2
Electrolyte	50 wt % aqueous NaOH
Operating temperature	135°C
Reference electrode	Hg/HgO/50 wt % NaOH at 25°C

Current density, ma/cm^2	Measured electrode potential, mv
0	+100 to +110 (drifting)
20	+35
40	—5
60	—53
80	—125

Cell Experiments

Several complete sodium-air cells were fabricated and tested at various stages of component development. Figure 2 shows one type of test cell prior to operation. The sodium feed tank (located to the left) is not yet connected to the sodium compartment (at the bottom of the cell). Connections on top are to aqueous NaOH and air feed and exit lines.

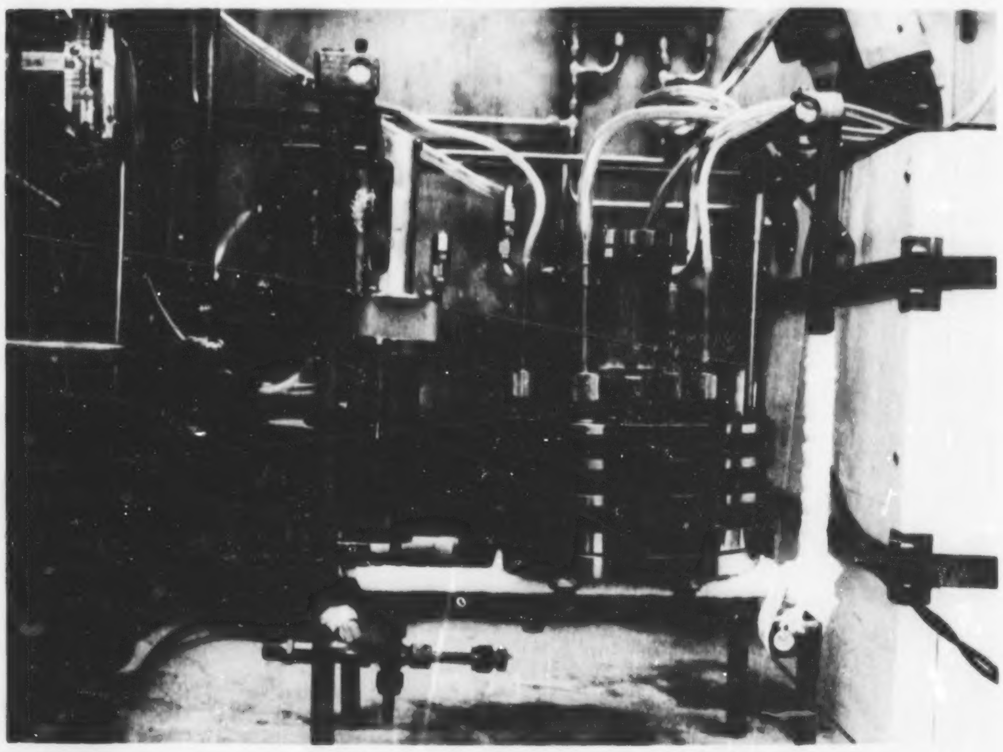

Figure 2. Sodium-air test cell.

Cells of 0.3- to 2.0-watt output have been operated successfully at 128° to 136°C for 50 to 150 hours. Typical data obtained with a cell of 1.0-watt nominal output (at 50 ma/cm^2 current density) are shown in Table 4.

EXPECTED PERFORMANCE OF THE SODIUM-AIR CELL BATTERY

The expected energy and power density values of a developed sodium-air cell battery were calculated on the basis of an engineering design study (Table 5). Design I is based on the assumption that a current density of 120 milliamperes per square centimeter can be achieved at an operating voltage of 2.1 volts. Experimental data indicate that this current density could be achieved with moderate improvements in the performance of various cell components. Design II is based on a current density of 200 milliamperes per square centimeter at the same operating voltage. Significant improvements in cell performance are needed to achieve this goal.

Table 4. SODIUM-AIR CELL OPERATING DATA

Cell Description

Component	Structural materials
Sodium compartment	Polypropylene
Molten salt electrolyte Matrix	Porous ceramic impregnated with molten salt
NaOH and air compartment	Teflon
Air electrode	Gold-coated nickel screen with porous Teflon backing; platinum loading 10 mg/cm^2

Active surface area of electrodes: 8 cm^2

Operating mode	Cell voltage, v	Current density, ma/cm^2	Power density, mw/cm^2
Open circuit	2.60		
Discharge	2.40	20	48
	2.30	50	115
	2.20	70	154
Charge	3.10	20	
	3.20	50	

Table 5. EXPECTED PERFORMANCE OF THE SODIUM-AIR CELL BATTERY

	Energy density, w-hr/lb		Nominal power density, w/lb	
	Design I[a]	Design II[a]	Design I[a]	Design II[a]
Theoretical energy density of reactants[b,c]	930	930		
Power density of cell battery[d]			60	100
Energy and power densities, complete battery assembly[c,e]				
Operating period: 4 hr	160	215	40	55
8 hr	240	300	30	37.5

[a] Design I based on a current density of 120 ma/cm^2 at 2.1-v operating voltage. Design II based on a current density of 200 ma/cm^2 at 2.1-v operating voltage.

[b] Based on reversible cell potential.

[c] One half of the weight of the stoichiometric oxygen requirement was used in calculating energy densities, because, on the average, only this amount will be present as chemically bound constituent in the aqueous electrolyte and thus contribute its weight to the system.

[d] Excluding weight of reactants stored outside of cells.

[e] Cell battery and reactants; weight of reactants includes weight of water required to dissolve the produced NaOH to form a 70 wt % aqueous solution,

Since the cell reactants are stored in tanks outside of the battery, the energy density of the complete battery assembly is a function of the operating time or the total amount of reactants carried. Two sets of data were calculated, for a 4-hour and an 8-hour operating period.

The energy efficiency of the cell on charge-discharge cycle at a current density of 120 milliampere per square centimeter is estimated to be about 60 percent.

SUMMARY

A novel compact sodium-sodium amalgam-air dual cell has been designed and operated. Cell components and complete cells of 0.3- to 2.0-watt output have been tested successfully at about 130°C operating temperature. Experimental data and preliminary engineering studies indicate that very high energy and power densities could be achieved with a fully developed sodium-air battery system. High expected performance and the advantages of relatively low operating temperature make this system very attractive for development as a power source for electric automobiles.

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ALUMINUM FUEL CELL FOR ELECTRIC VEHICLES

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SUMMARY

Although aluminum has long been recognized as a potentially superior battery anode material, its practical use has been precluded by excessive passivity in most electrolytes or by excessive corrosion in non-passivating electrolytes. Now we have succeeded in inhibiting the corrosion of aluminum in alkaline solutions reproducibly and over long periods of time while operating an experimental 60- to 80-watt aluminum-air battery at a current density of 40 to 50 amperes per square foot and 1.1 to 1.3 volts per cell. This battery has been performing satisfactorily in intermittent tests since April 1966.

Our experiments have generally confirmed the expected high energy capacity of alkaline aluminum-air batteries. In a highly conservative design based on present performance data, an over-all energy density of more than 200 watt-hours per pound was estimated for a 30-kilowatt, 240-kilowatt-hour power source including all accessories. Considerably higher densities should be achievable with moderate development effort.

The chemical rechargeability (by anode and electrolyte replacement) of our aluminum-air battery should constitute an important advantage for vehicle propulsion in that no overnight recharging would be required, nor would any megawatt power outlets be needed for rapid electrical recharging. Other advantages, such as a 1,000-mile driving range between electrode refuelings, exceptional safety, functional superiority, and over-all economy should allow aluminum-driven automobiles not only to compete fully with but to far surpass present cars.

INTRODUCTION

The fuel cell described here is unique in that it uses solid aluminum rather than a hydrogen-containing fluid as its chief anode reactant. It also differs from other metal-air batteries in that it is chemically rather than electrically rechargeable, and also provides for control of the voltage and power output through adjustment of the electrolyte level or of the depth of electrode immersion. Of course, zinc-air batteries with replaceable zinc anodes have been used for special applications and are even considered for motor vehicle propulsion. We propose to show however, that for the requirements of broad-purpose passenger automobiles such as those currently in use, the aluminum fuel cell appears to provide a practical, economical, and otherwise adequate primary electrochemical power source, potentially capable of competing with internal combustion power within the next few years.

Table 1. ELECTROCHEMICAL COMBUSTION ENERGY DENSITIES

Fuel	Faraday-volts/cm^3		Kw-h/lb fuel		Remarks
	Theor.	Pract.	Theor.	Pract.	
Liq. H_2	0.087	0.06	14.9	2.4	
Liq. NH_3	0.18	?	2.0	?	Require prohibitive catalyst area
N_2H_4	0.16	0.1	2.0	0.7	
Gasoline	0.24-0.3	0.09-0.12	5.0	2.0	
C	0.6-1.2	?	4.1	?	
Li	0.32	?	7.4	?	Too expensive
Be	1.13	?	7.8	?	
B	1.31	?	6.6	?	Poor conductor
Na	0.166	0.09	2.1	1.1	Too bulky
Mg	0.51	?	3.5	?	Poor current efficiency
Al	0.87	0.36	3.9	1.6	
Ca	0.31	?	2.4	?	Poorer than Al
Zn	0.43	0.28	0.74	0.5	Poorer than Al

In Table 1 we speak of "electrochemical fuel" rather than "anode reactants" to emphasize that neither the weight of oxygen nor that of water need be considered in preliminary energy-density comparisons as long as the latter substances are abundant and readily available from the surroundings. If we can seriously consider electrically rechargeable vehicles with a driving range of merely 50 miles for urban applications, then we should not object to replenishment with water at 200-mile or even at 100-mile intervals, especially if the main fuel charge could last for 500 or 1,000 miles. The combustion energy densities based on the weight of fuel alone may therefore provide fairly meaningful figures of merit for the best available electrochemical fuels.

Table 1 shows that aluminum is one of the most energetic fuels in terms of both volume and weight. On a volume basis aluminum is fourth highest, and its combustion energy content is close to two-thirds of the highest possible value. On a weight basis aluminum is seventh highest after hydrogen, beryllium, lithium, boron, gasoline, and carbon. Beryllium and lithium can be immediately excluded as economically prohibitive for large-scale primary fuel requirements. Boron is a poor conductor and has otherwise unsatisfactory anode characteristics, at least in the present state of the art. This brings aluminum again up to fourth place, after liquid hydrogen, gasoline, and carbon, with its practical energy content per unit weight again amounting to two-thirds of the highest possible value.

Our analysis thus far fully covers all the readily oxidizable elements in the first two rows of the periodic table. As the elements get heavier, the energy densities become obviously poorer. Nevertheless, to ascertain that the attractive energy density of aluminum is not somehow outweighed by some of the other potential fuels, let us review the remaining metals in the third and fourth rows of the periodic table that might be considered for metal-air batteries. Although sodium may provide a respectable energy density on a weight basis, it is bulky. In addition, its use in amalgamated form and possibly also at high temperatures renders it far less practical than aluminum. Magnesium might come closest to aluminum in terms of theoretical energy per unit weight and per unit volume. Yet, in the strongly alkaline or acidic electrolytes required for air cathodes, magnesium poses much more severe passivation and corrosion problems than are encountered with aluminum. The same objection may apply to calcium. Thus, zinc is left as the only material having sufficiently attractive anode characteristics to be worth further consideration.

COMPARISON OF ALUMINUM-AIR AND ZINC-AIR CELLS

Our system resembles the well-known zinc-air batteries in several respects. We use aluminum anode sheets between two air cathodes just as in the Leesona-Moos type of primary battery described by Palmer or as in the General Dynamics type of secondary battery described by Ragone, both in this volume. The reactions are of the same type:

metal + oxygen + water → metal hydroxide.

An electrolyte circulating system has also been used with aluminum-air cells since 1960 (Zaromb and Foust, 1962). There are several differences, however. No anode grids are required, since the aluminum is to be consumed entirely. No separators are used; it is a free electrolyte system. The energy per reactant weight is at least two-fold higher for aluminum, as shown in Table 2. Theoretically, aluminum would yield a 3 times higher energy density. In practice, however, the usual operating cell output may be about 1.3 volts with zinc and around 1.2 volts with aluminum, which still yields the 2:1 ratio in favor of aluminum shown in the last column of Table 2. Applying Mr. Shair's (in this volume) rule of thumb (approximately 20 percent of the theoretical energy density for the density to be expected in practice) to Table 2, one reaches an estimate of 160 to 400 watt-hours per pound for a practical aluminum-air battery. On the basis of the 2:1 ratio in favor of aluminum, one might double the energy densities available from present or projected zinc-air batteries, 60 to 100 watt-hours per second for secondary cells and 150 watt-hours per pound for primary cells, and thus again arrive at an estimate of 160 to 300 watt-hours per pound for practical aluminum-air batteries. These estimates are generally confirmed by the experimental data and design analysis presented in the following sections and summarized in Table 3.

The well-known and quite satisfactory anode performance of zinc, its relatively slow corrosion rate in alkaline solutions, and its electrical rechargeability have contributed to the widespread acceptance of zinc anodes for miscellaneous low-power electrochemical devices. But, for long-range portable power sources in the range of 10 to 30 kilowatts, we believe that electrical recharging is inferior to chemical recharging. Moreover, both the anode performance and the corrosion behavior of aluminum can be controlled.

Table 2. COMPARISONS OF ALUMINUM AND ZINC CELLS

	Total	Without O_2		Kw-h/(lb M H_2O)	
	g/F	g/F	cm^3/F	Theoretical	Practical
Al	26.0	18.0	12.3	1.94	0.8
Zn	49.7	41.7	13.5	0.58	0.4

$$z^{-1}M + \tfrac{1}{4}O_2 + \tfrac{1}{2}H_2O \rightarrow z^{-1}M(OH)_z$$

M = Zn or Al; z = 2 or 3

Table 3. WEIGHT ANALYSIS OF A 30-KILOWATT, 2[illegible] KILOWATT-HOUR, ALUMINUM-AIR BATTERY

Weight, lb	Scheme I	Scheme II	Scheme III
Anode charge	150	150	300
Electrolyte charge	650	350	500
Uncharged battery assembly	200	200	200
All accessories	200	200	200
Total weight, lb	1,200	900	1,200
Component life, kw-h			
Electrolyte replaced and ppt removed after	240	120	120
Anodes replaced after	240	240	480
Energy density, w-hr/lb, based on			
anode replacement intervals	200	267	400
electrolyte replacement intervals	200	133	100
Power, kilowatts			
Average power	30	30	30
Peak power without cathode boosting provision	45	45	45
Peak power with cathode boosting provision	>90	>90	>90
Power density, w/lb			
Average power density	25	33	25
Peak power density without cathode boosting	38	50	38
Peak power density with cathode boosting	>76	>100	>76

Design based on:

(1) 1.2 Faraday-volts/9 g Al or 1600 w-hr/lb Al.

(2) 4.3 lb initial electrolyte/lb Al consumed.

PERFORMANCE OF EXPERIMENTAL 70-WATT ALUMINUM-AIR BATTERY

The experimental battery apparatus is shown in Figure 1. Ambient air is pumped first through a concentrated KOH solution, which removes CO_2 and humidifies the air, and then to a manifold leading to 14 parallel porous cathode compartments. The air pressure within the cathode compartments is usually about 2 to 3 inches of water, comparable to the maximum height of electrolyte within the cell compartments during battery operation. The anodes are held by a plastic cover that fits exactly over the cathode assembly.

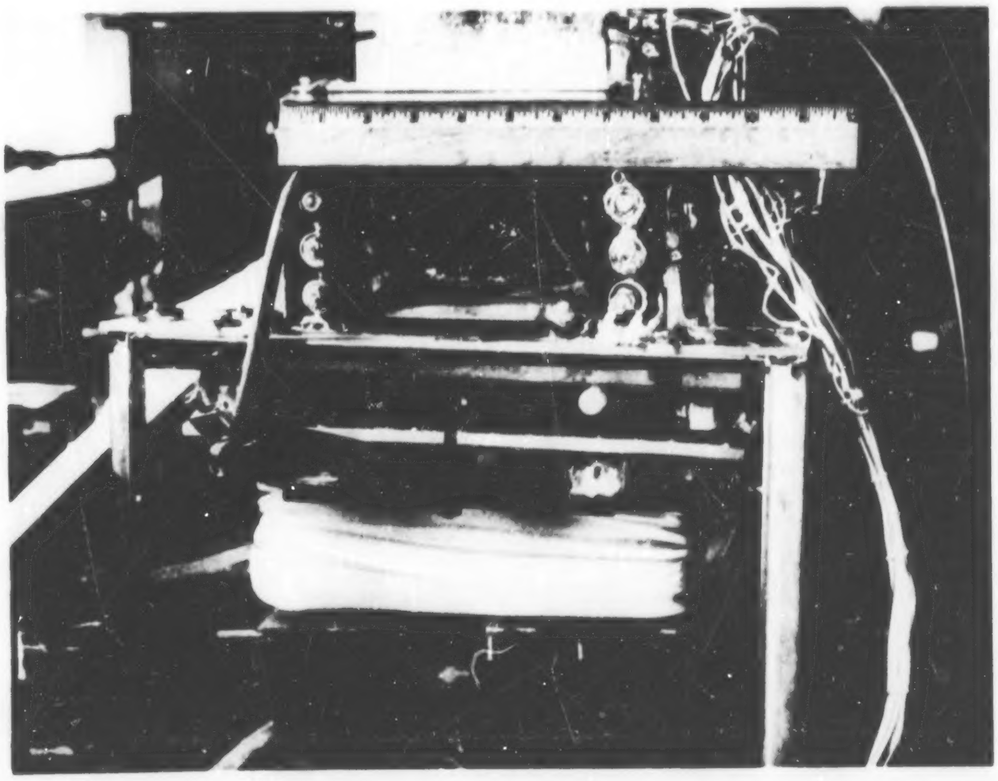


Figure 1. Experimental 70-watt aluminum-air battery.

The electrolyte level within the cell compartments is controlled by a small lab-jack, which raises or lowers a base plate pressing against a collapsible electrolyte reservoir. The latter also collects the $Al(OH)_3$ battery reaction product. This reservoir is easily unclamped from or clamped onto the base of the battery during precipitate removal and electrolyte replacement.

When no power is drawn, the electrolyte is allowed to drain into the reservoir to prevent exposure and corrosion of the aluminum anodes. For battery operation the reservoir is collapsed partly, as shown in Figure 1, so that electrolyte is forced into the battery compartments. The electrolyte is also pumped through a heat exchanger to remove the heat dissipated in the battery reaction.

Any hydrogen evolved as a result of anode corrosion is channeled through a single gas-outlet tube connected to the battery cover. This outlet tube constitutes a simple and rapid corrosion detector; the nascent hydrogen formed in any corrosion reaction is readily detectible through its pungent odor, especially when it is all channeled through a single outlet. The occurrence or absence of any significant corrosion could thus be diagnosed, and the corrosion could be prevented or kept to reasonable levels through proper battery operation. We have acquired enough understanding of the corrosion reaction to prevent or induce corrosion within the same battery, reversibly and at will.

Our battery discharge curves tend to confirm the absence of a significant corrosion rate under our experimental conditions. Figure 2 is representative of the kind of output voltage, current, and power drawn from an immersed electrode area of 1,400 square centimeters with anodes 0.05 centimeter thick consumed simultaneously from both sides. At 100 percent current efficiency and an average current density of 50 milliamperes per square centimeter, the anodes would be expected to last for 4 hours, or about 700 coulombs per square centimeter. Actual integration of the current curve of Figure 2 yields around 500 coulombs per square centimeter. Since about one-third of the original anode thickness was left at the end of the run, the figures given here are roughly consistent with nearly 100 percent efficiency.

The data in Figure 2 were obtained in June 1966. Data from an experiment performed in March 1967 are shown in Figure 3. The same battery and experimental apparatus were used as in the earlier runs; however, the anodes were 0.3 centimeter thick and cut narrower. The immersed electrode area was therefore only 1,250 square centimeters. Nevertheless, the average power output was still between 60 and 70 watts, at around 40 milliamperes per square centimeter and 1.2 volts per cell. Similar results were obtained in even more recent experiments (June 1967). Thus, no observable deterioration in battery performance occurred during a 12-month period.

The run of Figure 3 was designed to determine the minimum weight ratio of electrolyte to aluminum required for satisfactory continuous battery operation. To obtain this information it was most expedient to allow 2 kilograms of aluminum to corrode away in an initial 8-liter volume of 3 M KOH solution. Additional water was added to make up for evaporation losses. After complete dissolution of the aluminum, the total volume was again brought to 8 liters. The final mix therefore contained around 5.8 kilograms $Al(OH)_3$ plus 6.7 kilograms 4 M KOH solution. This mix was then re-introduced into the electrolyte reservoir, and the run was completed.

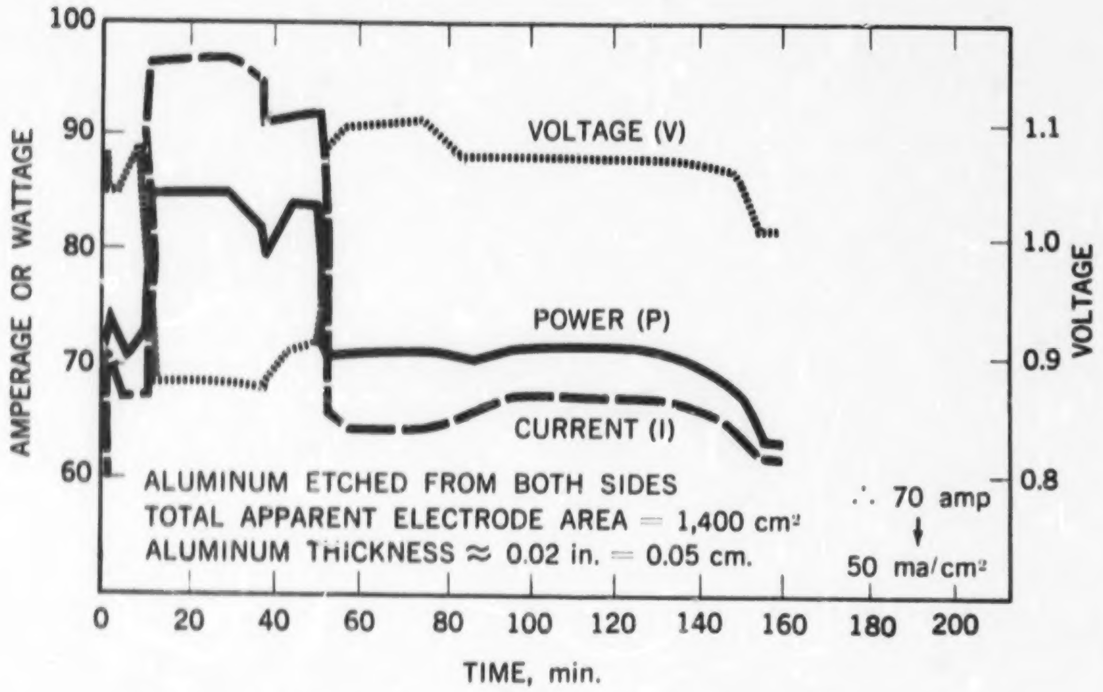


Figure 2. Typical performance of a 70-watt aluminum-air battery with thin anodes. Kinks in curves correspond to load adjustments (June, 1966).

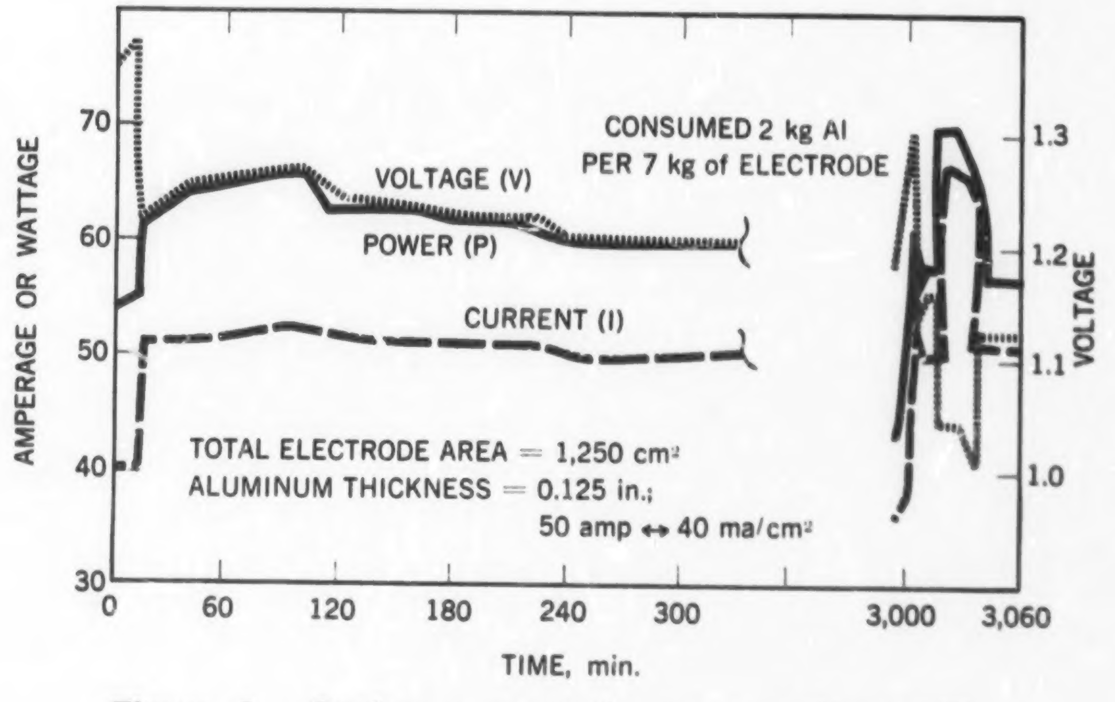


Figure 3. Performance of the same battery with thick anodes of smaller area (March, 1967).

Figure 3 shows that the battery performance near the end of the run was not much worse than at the beginning. Hence, the residual electrolyte weight need not exceed 3.3 pounds per pound of aluminum consumed, and the corresponding initial electrolyte weight need not exceed 4.3 pounds per pound of aluminum.

In these experiments we obtained about 1.2 faraday-volts per gram equivalent (9 grams) of aluminum, or 1,600 watt-hours per pound of aluminum at current densities of at least 40 milliamperes per square centimeter. Further, such performance could be obtained even without replenishment of electrolyte or of water if the initial charge included 4.3 pounds of electrolyte per pound of aluminum consumed.

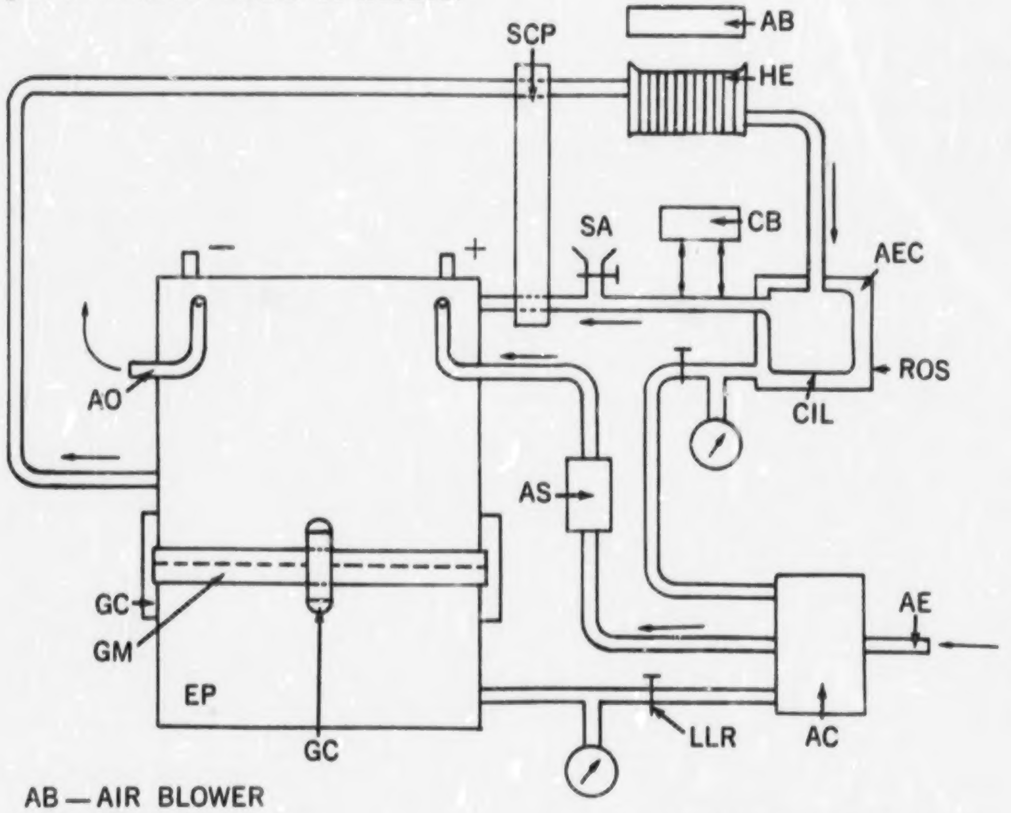
In addition, our single-cell experiments have yielded considerably higher current densities and output voltages with somewhat more active aluminum alloys. Unfortunately, our present stock of alloys is not easily adaptable for testing in the multicell battery of Figure 1. On the basis of our experience to date, however, we expect no serious difficulty in obtaining at least 1.2 volts per cell at 100 milliamperes per square centimeter and nearly 100 percent current efficiency with at least one type of a readily available aluminum alloy.

SIGNIFICANCE OF EXPERIMENTAL RESULTS

A design analysis has been performed for a 30-kilowatt aluminum-air power source. The block diagram of Figure 4 shows all the required accessories. The air supply system, including a compressor, air scrubber, and connecting tubes or manifolds, is essentially similar to those used in other fuel cells. The electrolyte circulating system, including a heat exchanger and auxiliary reservoir, is also similar to those generally used. A multichannel pump, possibly of the peristaltic type, is proposed for the purpose of eliminating leakage currents between series-connected cells. Furthermore, the electrolyte volume in the reservoirs can be readily altered by application of air pressure within spaces enclosed by collapsible inner linings and rigid outer shells. The electrolyte level in the battery assembly is thus pneumatically controlled by a simple air-pressure regulator. This also provides a simple, light, and inexpensive means of controlling the current, voltage, and power output without recourse to any electronic circuitry.

The aluminum hydroxide precipitate formed in the battery reaction is to be collected in one of the electrolyte reservoirs and preferably returned for credit at a refueling station. Alternatively, the precipitate may be disposed of whenever fresh water is added to the system. At least two simple arrangements are being considered for ejecting the precipitate safely and conveniently.

The cathode boosting means shown in Figure 4 may consist of a solution of oxidant, such as hydrogen peroxide, which may be injected into the electrolyte entering the battery assembly. The chief power limitation of the oxygen or air electrode is known to be associated with the low solubility of oxygen in aqueous alkaline electrolyte. Hence, during periods of peak power demand it may be desirable to inject an alternative oxidant into the electrolyte. Although such oxidant would have an adverse effect on hydrogen anodes, we have found no deleterious effect and even an enhancement of the activity of aluminum anodes upon introduction of around 1 percent H_2O_2 into the electrolyte. This simple method of boosting the cathode performance should double the peak power output and thus meet all peak power requirements; no auxiliary batteries or other auxiliary power sources would be needed.



AB — AIR BLOWER
AC — AIR COMPRESSOR
AE — AIR ENTRY
AO — AIR OUTLET
AS — AIR SCRUBBER
BA — BATTERY ASSEMBLY
CB — CATHODE BOOSTING MEANS
EP — ELECTROLYTE AND PRECIPITATE CONTAINER
GC — GASKETING CLAMPS

GM — GASKETING MOLDING
HE — HEAT EXCHANGER
SA — SIDE ARM
AEC — AUXILIARY ELECTROLYTE CONTAINER
CIL — COLLAPSIBLE INNER LINING
LLR — LIQUID-LEVEL REGULATOR
ROS — RIGID OUTER SHELL
MCP — MULTI-CHANNEL PUMP

Figure 4. Block diagram of a proposed aluminum-air power source.

Since the required accessories do not otherwise differ appreciably from those in similar systems, we can formulate a weight analysis of our proposed power source by referring to the weights quoted by Dantowitz and Gaddy for an operational hydrazine fuel cell. The required accessories for 20-kilowatt and 40-kilowatt hydrazine systems weigh 185 pounds and 235 pounds, respectively. Hence, the accessory weight for a 30-kilowatt system may amount to around 200 pounds. The remaining weight evaluation in Table 3 is derived directly from the experimental data presented in the preceding section.

The three schemes in Table 3 may again demonstrate the propriety of disregarding the weight of water in the preliminary energy-density comparisons of Table 1. The initial electrolyte charge will last for a complete 8-hour operation at average load. Hence, a vehicle traveling at 60 mph at average power would have a range of 480 miles between refueling stations. By another scheme, however, the range between stations would be the same, but the driver would have to stop off midway for a fresh electrolyte charge. The total fuel cell weight is thus reduced by around 25 percent, and the peak power density is correspondingly increased to around 50 watts per pound without recourse to cathode boosting, and possibly to more than 100 watts per pound with our cathode boosting provision.

Where the power density achievable by the first scheme may be entirely adequate, one can easily increase the range between refueling stations to around 1,000 miles by doubling the aluminum charge and still keep the initial electrolyte charge down to 500 pounds, of which 150 pounds would be in form of three separate 50-pound dry KOH cartridges providing fresh electrolyte upon addition of water at successive 200- to 300-mile intervals.

Although the energy and power densities given by Table 3 are already attractive, they do not reflect the important weight savings provided by the simple pneumatic power control already mentioned. The power controller used with the 20- to 40-kilowatt hydrazine fuel cell weighs 300 pounds, and even if this weight is eventually reduced by a factor of 2 it would still represent around 15 percent of the total weight of the power source. Since an air pressure regulator need not weigh more than 2 pounds, our power control weight is clearly negligible. Hence, the 15 to 30 percent saving on the weight of electronic controls becomes equivalent to a corresponding further increase in effective energy and power densities.

One might argue that electronic inverter circuitry might be required in any event for use with alternating-current motors, which weigh only about 1 pound per horsepower, whereas present commercial direct-current motors weigh more than 5 pounds per horsepower. At least one lightweight direct-current motor has been developed with an estimated weight of around ½ pound per horsepower (Zeisler, 1964). This motor also requires lower voltages, 2 to 5 volts, which may further simplify the fuel cell design, e.g., by reducing the required number of separate electrolyte pumping channels. The heavy bus bars required with large currents could be kept down to a reasonable level by placing the battery close to the motor. For example, a rod of copper 1 square centimeter in cross section and 100 centimeters long weighs less than 2 pounds. The type of homopolar direct-current motor reported by Zeisler apparently would provide not only an adequate but a highly desirable combination with any type of cell.

NEAR-TERM AND LONG-TERM PROSPECTS OF THE ALUMINUM FUEL CELL

In addition to its important functional advantages, the aluminum fuel cell appears to be economically attractive both immediately and long term. At current prices, the cost of aluminum fuel (25 cents/lb) less the cost of the recoverable $Al(OH)_3$ product (around 5 cents/lb $Al(OH)_3$ or 10 to 15 cents/lb Al) may be already comparable to or lower than the average cost of gasoline consumed in present internal-combustion engines for the same motive energy yield. In competitive mass consumption the costs of aluminum should come down, since the over-all aluminum consumption and recovery cycle would utilize the cheapest available resources—carbon, and the cheapest available electricity (usually processed directly near a hydroelectric power plant) —at a fairly reasonable overall energy efficiency. Modern aluminum reduction plants can operate at current efficiencies of at least 90 percent and less than 4.1 volts per cell (Oehler, 1963). Hence, the fraction of electric energy input that may be regained in form of motive power should amount to at least 90 percent times 1.2 volts divided by 4.1 volts, or 26 percent. In addition, the salvageable heating value of the heat generated in the battery may considerably increase the effective efficiency in cold weather.

The production of aluminum near sources of cheap electricity, i.e., in predominantly rural areas, would also prevent further introduction of smoke-stack pollutants from power plants in urban surroundings. Although aluminum reduction plants do inject pollutants into the atmosphere, their emissions should be much more readily amenable to control than motor vehicle exhausts or flues in urban areas. In addition, the total amount of carbon dioxide that would be introduced into the earth's atmosphere by each complete aluminum reduction-consumption cycle can easily be shown to be around half of what might be produced in a few decades for comparable energy production by hydrocarbon fuel cells.

This discussion thus far has failed to point out some of the obstacles to an early realization of practical and competitive aluminum-driven vehicles. The present high cost of air cathodes may constitute the chief and perhaps only genuine technical-economic barrier. This high cost cannot be due only to catalyst requirements, since the silver required for satisfactory cathodes need not cost even $1 per square foot. We believe that at considerably greater cathode costs ($10/ft^2) the aluminum fuel cell may start competing with gasoline engines. The present costs of $50 to $100 per square foot of cathode area are thus only 10 times higher than what we regard as the maximum costs allowable for motor vehicle applications, and these costs may be attributed chiefly to the small production scale and to initial development outlays. Discussions with cathode suppliers lead to the conclusion that a cost of $5 per square foot on a mass production scale may be a realistic forecast.

One must also take cognizance of past failures to develop practical aluminum batteries (Brown, 1893; Sully, 1897; Polcich, 1926; Vince, 1933; Ruben, 1933, 1951, 1952; Stokes, 1955; Lozier et al., 1959, 1961; Sargent, 1951; Zaromb, 1962). These past attempts were, however, directed toward small cells for low-power applications where the use of auxiliary mechanical accessories could not be considered. It is chiefly for high-power and high-energy-storage applications that the aluminum fuel cell is attractive.

Other problems have been met since the inception of this work some 8 years ago (Zaromb and Faust, 1962; Zaromb, 1962; Bockstie, Trevethan, and Zaromb, 1963). Throughout, we have had to steer a narrow course between passivation of the anodes and excessive corrosion. We believe we now have enough knowledge of these difficulties and of how to circumvent them to be confident that a practical, aluminum-driven vehicle will sooner or later make a successful appearance.

ACKNOWLEDGEMENTS

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PERFORMANCE AND ECONOMICS OF THE SILVER-ZINC BATTERY IN ELECTRIC VEHICLES

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Two principal arguments have been advanced for the electric car: freedom from pollution of the air, and economy. The pollution argument is clear enough; each gasoline-powered car emits an estimated ton of pollutants each year. The concentration of pollutants in New York approached the crisis level last Thanksgiving (1966). With the increase in the number of cars, the crisis level may be surpassed at any time. Although engine manufacturers are working on reduction of emissions, there is no guarantee that the achievements in this direction will not be swamped by the increase in the concentration of cars in urban areas. Since the internal combustion engine produces more than half the total pollution in urban areas, it is evident that replacement by electric cars could result in a substantial decrease in pollution.

Evaluation of the economics of the electric car is more complex. Additional factors such as range, speed, acceleration, life, and even method of financing must be taken into account. To start with, consider the energy-storage capacity of the batteries that are now used for various purposes and that might be used to power an electric car. The energy densities for the various batteries in terms of watt-hours per pound are (FPC, 1967) lead-acid, 8 to 12; nickel-iron, 11; nickel-cadmium, 12 to 14; silver-cadmium, 30; and silver-zinc, 40 to 60.

Lead-acid, with the lowest energy density of the lot, has had the field to itself since 1870, when Sir David Solomons built the first electric vehicle. The business burgeoned, and between 1900 and 1915 over 100 manufacturers were in operation. By 1912, the business amounted to 6,000 passenger and 4,000 commercial vehicles yearly. Range was 20 miles and top speed was 20 mph. It is worth emphasizing that traveling at top speed cuts the range, so that top speed and maximum range cannot be achieved in combination. This is true of the other batteries and also of internal combustion.

The cost ranged from $2,600 for a Baker Electric to $5,500 for a Borlund Electric. It would be interesting to calculate the cost per mile in today's dollars for the Borlund Electric.

After 1914 the manufacture and sale of electrics fell off, and internal combustion took over the market. By 1933, electrics had gone off the market (Ference, 1967). Nevertheless, during this period a number of concepts were proposed that may prove important today. To eliminate the energy loss at the differential, the rear wheels were driven by individual motors. Charging at metered outlets and exchange of exhausted batteries for fresh batteries at service stations were both proposed.

In this country lead-acid batteries are now used for the propulsion of fork-lifts, of which about 100,000 are in use. The battery-powered fork-lifts are used in enclosed spaces in which internal combustion fumes cannot be tolerated.

In England there are about 40,000 battery-powered urban delivery vans, and 60,000 fork-lifts. We see, then, that where the daily range is sufficiently limited, even lead-acid batteries can meet the needs.

With reference again to batteries mentioned earlier, it is evident that nickel-cadmium and nickel-iron do not give a sufficient increase in energy density over lead-acid to warrant their use in passenger cars. Nickel-iron batteries are extremely long-lived, however, and thus are suitable for powering trucks. Some of the batteries originally put into use around 1910 are believed to be still in operation.

Silver-cadmium, from the standpoint of energy density, is far superior to the other three batteries; however, it is by far more expensive. It is also substantially more expensive than silver-zinc. The silver-zinc battery not only tops the list in energy density but is also a high-rate battery. The General Motors Electrovair II reached a speed of 80 mph, powered by Yardney silver-zinc batteries.

The first cost of silver-zinc appears high relative to lead-acid, but a more significant parameter is the cost per mile. To calculate this, we use the data obtained by installing four Yardney Electric batteries in a modified Renault Dauphine automobile. The car was originally modified for use with lead-acid batteries, and was fitted with a 7.1-horsepower direct-current motor. The Yardney batteries were designed for aircraft use and therefore were not optimum for the car. Each consists of fourteen 85-ampere-hour cells, which give about 120 ampere-hours when new. Figure 1 shows typical discharge curves for a 100-ampere-hour cell, which is very similar in construction and of only slightly larger capacity. Figure 2 shows voltage as a function of current density. This curve makes it possible to predict wattage as a function of current.

The car was run on a flat road; both voltage and current were observed. Wattage is plotted as a function of speed in Figure 3. Note that the wattage at each speed varied over a substantial range. Evidently wind is a factor, with low wattages indicating a following wind and high wattages a head wind. To estimate the energy expended in traveling 1 mile, a value for 40 mph can be taken from the graph, a value from the middle of the zone. A speed of 40 mph requires 6,500 watts. With the proper mathematical manipulation we find that 1 mile requires 160 watt-hours.

At a battery voltage of 75, the number of ampere-hours required per mile is 160/75 or 2.1. For city driving, an average speed of 25 mph is more likely. At this speed the wattage is about 1,700 and the voltage about 80. This works out to 68 watt-hours and 1.05 ampere-hours per mile. On this basis the range would be 85/1.05 or 81 miles.

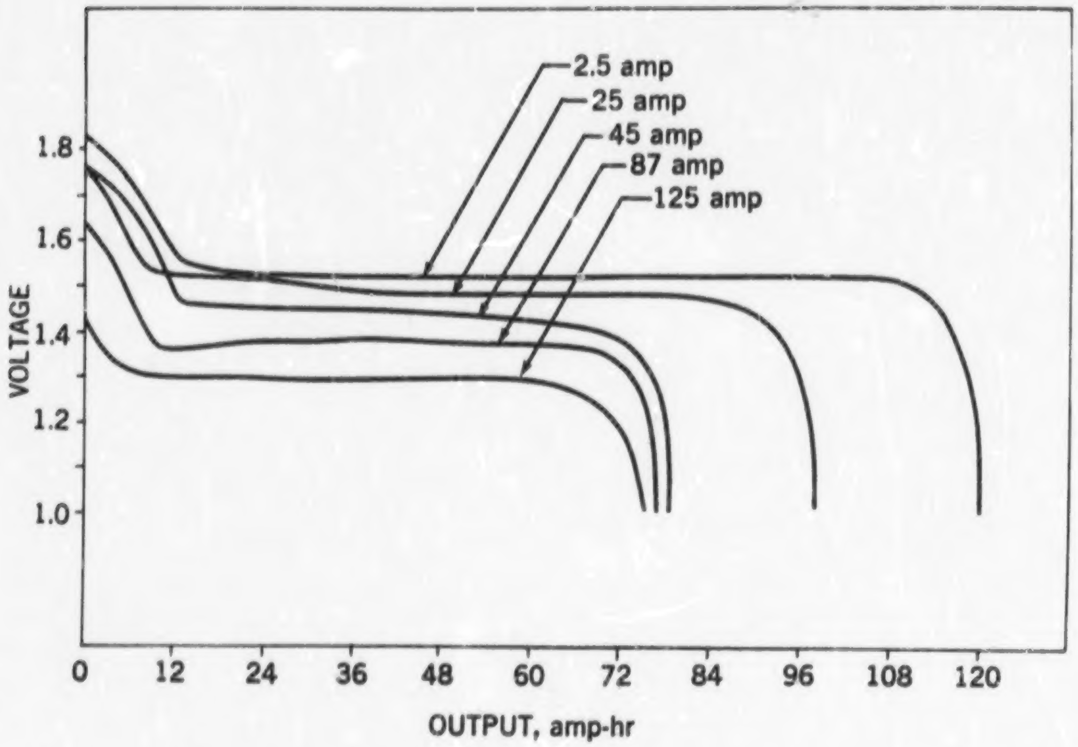

Figure 1. Typical discharge curves for 100-ampere-hour cell.

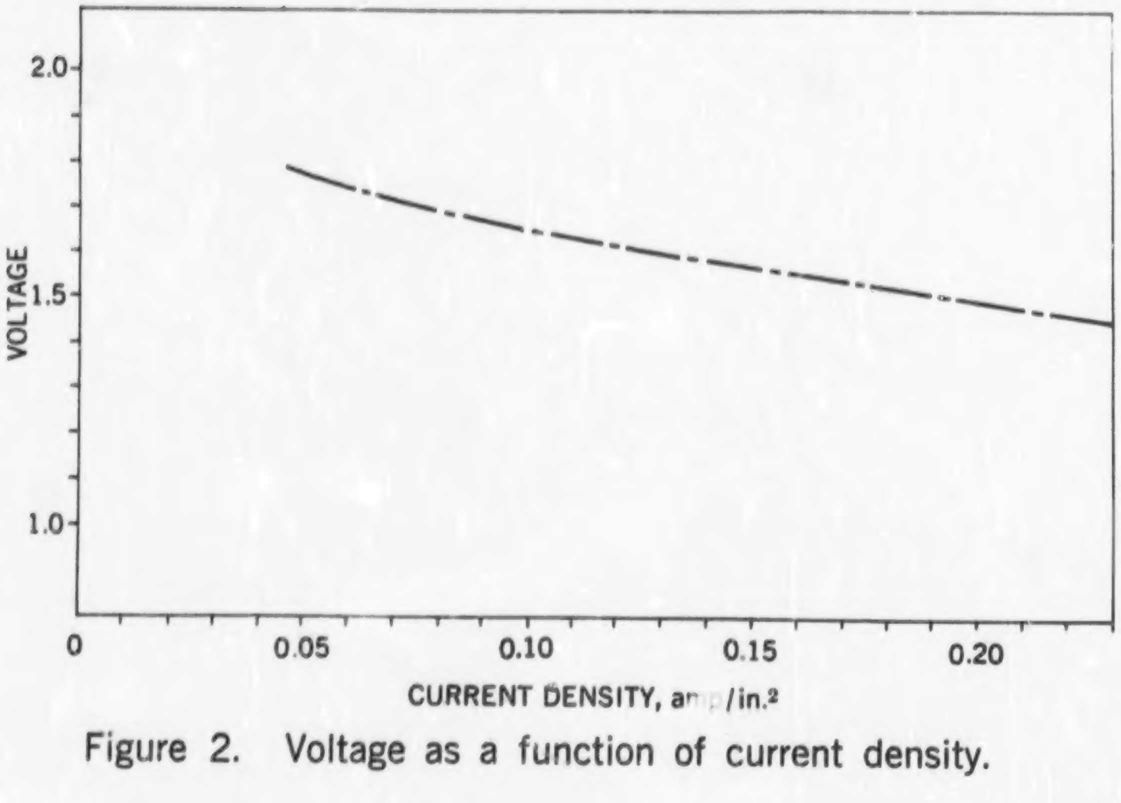

Figure 2. Voltage as a function of current density.

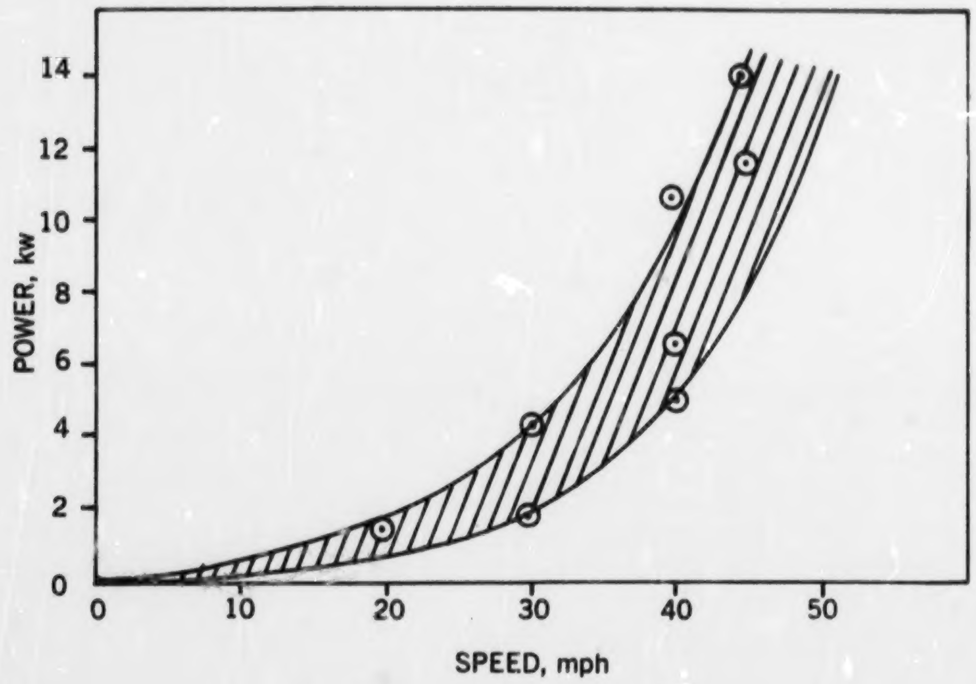

Figure 3. Wattage as a function of vehicle speed.

In practice the range is about 77 miles. This range gradually decreases as the battery ages and is shorter at higher speeds.

The four batteries, including metal cases, weigh 240 pounds. The weight can be cut by 30 pounds through the use of plastic cases. The car, without batteries or occupants, weighs 1,335 pounds and is not streamlined. Maximum speed is 55 mph. The motor is 7.1 horsepower and is series-wound. With the car on blocks, turning the wheels at 40 mph requires 2 horsepower.

The speed control in this model is the one that was installed when it was originally fitted for lead-acid batteries and consequently is primitive. The control was not changed for the tests with silver-zinc because the objective was to obtain performance data on the battery. For the same reason, the low-power motor also was retained. The control can achieve six speeds by placing the four batteries in parallel, series-parallel, or series, and through the use of a series resistor (at bottom speed) and a field shunt.

As stated earlier, the batteries described were not designed for use in the car — they occupied only about half the available space in the front and rear trunks. Yet the data can serve as the basis for a more suitable design and for cost estimates. The number of cells will be taken as 60 because this number can be charged directly from 110-volt alternating current, with a suitable rectifier, of course. The space available in the car is adequate for 60 cells of any capacity up to about 250 ampere-hours; the technology is available for a battery of almost any size.

Let us start with the assumption that a second family car will be driven about 50 miles per day. Also, assume that a safety factor of 2 in the range must be provided. This will require that battery capacity be increased to 124 ampere-hours.

To compare the costs of operating internal combustion and electric vehicles, we must make some basic assumptions:

Internal combustion vehicle

Retail cost, $3,000.

Life, 6 years at 12,500 miles per year. This figure is based on 50 miles per day, 5 days per week, 50 weeks per year. Gasoline mileage, 13 miles per gallon at $0.35 per gallon, or 2.7 cents per mile.

Battery-powered vehicle

Retail cost, $2,500 without battery. Cost is lower than that of the internal combustion car because cost of engine, transmission, and auxiliaries is subtracted. Cost of motor, controls, and charger is included.

Life, 10 years at 12,500 miles per year. Car life is assumed longer than for internal combustion because the system is much simpler. Electricity mileage, cost of electricity is $.01 per kilowatt-hour and charge wattage efficiency is 50 percent. At 160 watt-hours per mile, cost is 0.33 cents per mile.

Retail cost of the battery, exclusive of silver, is estimated to be $700 to $900. Our accounting department has suggested that the lower figure be used for calculations. Life is taken as 2 years when the vehicle is operated for 12,500 miles per year and as 4 years for 7,500 miles per year.

The silver can be leased or rented. This is now the practice with batteries for fork-lifts. The silver can be re-used indefinitely with virtually no loss, and can therefore be regarded as indestructible collateral for a loan. This places its cost in a different category from that for the remainder of the battery and the vehicle.*

Battery life, on the basis of laboratory data, can be taken as 500 cycles at 50 percent depth of discharge. The cycle-life is extended as the depth of discharge is decreased. Moreover, recent developments in battery construction have demonstrated substantial increases in cycle life over that quoted here

With these assumptions, the cost of operating the battery-powered vehicle is somewhat lower than that of operating the internal combustion vehicle.

The costs are compared in Table 1 for mileage of 12,500 per year. The picture changes if the daily mileage is lower. The life of the battery will be substantially longer at the shallower depth of discharge. We now examine a new set of assumptions. Traveling 30

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*Cost estimates based on silver at pegged price of $1.29 per ounce.

Table 1. COST COMPARISON BASED ON 12,500 MILES PER YEAR

	Internal Combustion		Battery Power	
Fixed costs				
Depreciation	$500		$250	
Battery	0		350	
Insurance	200		250	
License and taxes	20		20	
	720	720	870	870
Operating costs				
Gasoline	337		0	
Silver rental, 9%	0		96	
Oil, grease, tires, etc.	140		75	
Charging	0		41	
	477	477	212	212
Cost per year		1,197		1,082
Cost per mile		9.6¢		8.7¢

Table 2. COST COMPARISON BASED ON 7,500 MILES PER YEAR

	Internal Combustion		Battery Powered	
Fixed costs				
Depreciation	$500		$250	
Battery	0		175	
Insurance	200		250	
License and taxes	20		20	
	720	720	695	695
Operating costs				
Gasoline	203		0	
Silver rental, 9%	0		96	
Oil, grease, tires, etc.	84		45	
Charging	0		25	
	287	287	166	166
Cost per year		1,007		861
Cost per mile		13.4¢		11.5¢

miles per day, 5 days per week, 50 weeks per year yields 7,500 miles per year. Battery life increases to 4 years. Table 2 presents the cost comparison for 7,500 miles per year. At this mileage, the battery-powered vehicle provides an even greater cost advantage.

Since the assumptions on which these accountings are based involve some uncertainties, it would be overstating the case to claim that battery power is substantially cheaper than gasoline. Nevertheless, it appears that silver-zinc battery power is no more expensive than gasoline power, and if anything is cheaper. Consequently, cost is no obstacle to the use of silver-zinc for low-mileage applications. Since batteries emit no pollutants, silver-zinc offers the possibility of a fast start toward eliminating the pollution blight.

In concluding, I should mention that work is proceeding in a number of laboratories on systems of still higher energy density. Specific examples of couples under investigation are zinc-air, lithium-nickel halide, sodium-sulfur, and lithium-chlorine. Speaking for our own laboratory, I can say that progress on zinc-air is very satisfactory and we expect to present results before long.

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A SODIUM-SULFUR SECONDARY BATTERY

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INTRODUCTION

One of the major barriers to the general use of electric power in mobile applications is the inadequacy of the power source. This has been true for over half a century, yet the advantages that could be gained through the use of electric power are such that technological advances, as they occur, are continually reviewed for their potential in overcoming this barrier. A case in point is the widespread resurgence of interest over the last decade in fuel cells and high-energy-density rechargeable battery systems.

Research and development in this area has taken many paths and has had many origins. The result of one approach is the subject of this paper.

The work that will be described did not originate directly as a conscious search for a high-energy-density electrical power system, but is a product of the interaction of fundamental research in solid-state science and a continuing awareness of the major problems of the energy storage and conversion field.

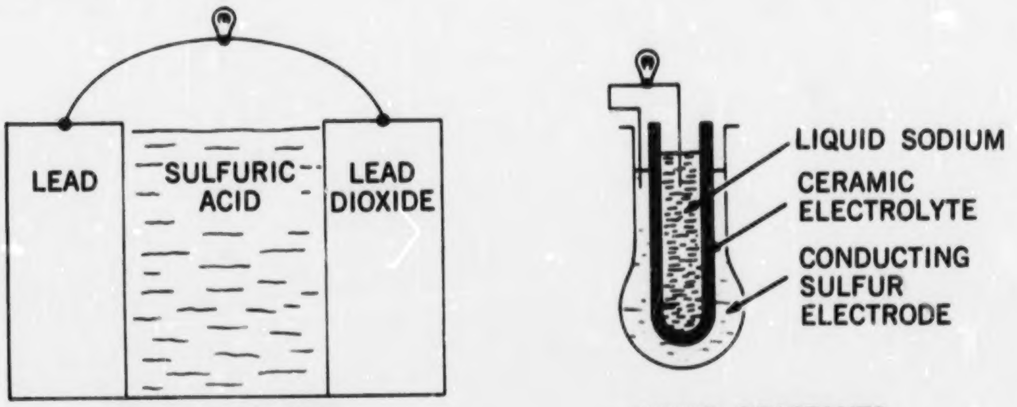
SOLID ELECTROLYTES

Common to all secondary cells is an ionically conducting membrane separating reactive materials. The reactive materials are constrained to combine by ion transport through the membrane and electron transport through an external circuit where the free energy change corresponding to the cell reaction is extracted as useful work. The fundamental idea in this concept of a sodium-sulfur cell is that of using a solid ionically (but not electronically) conducting membrane between reactants. When such a solid membrane, which takes the place of the usual liquid electrolyte, is also impermeable and inert to reactant materials in other than ionic form, the possibility exists of using energetic reactants in the liquid state. Molten electrodes suffer from no irreversible changes on charge-discharge cycling and often present fewer problems from polarization at phase interfaces.

Figure 1 compares the sodium-sulfur cell schematically with the common lead-acid cell. In the latter, electrons pass through the external circuit (where they do work) and ions through the sulfuric acid electrolyte to complete the reaction, which is essentially the oxidation of lead and the reduction of lead dioxide. The reactants and products are solid, and the electrolyte, liquid. In the sodium-sulfur system, liquid sodium, which serves as its own electrode, yields electrons to the external circuit, passes through the separator as a sodium ion, and reacts with liquid sulfur, which receives electrons from the external circuit, to form sodium sulfide, which is also kept liquid by operation at elevated temperature (300°C).

LEAD-ACID STORAGE BATTERY

FORD SODIUM BATTERY



SOLID REACTANTS, LIQUID ELECTROLYTE

On discharge, energy is extracted in external circuit while both electrodes and electrolyte undergo chemical change.

LIQUID REACTANTS, SOLID ELECTROLYTE

Current is carried by sodium atoms that give up electrons to external circuit, traverse solid ceramic electrolyte, and react with sulfur.

Figure 1. Schematic representation of sodium-sulfur cell and comparison with lead-acid cell.

THE SODIUM-SULFUR SYSTEM

Sodium and sulfur are attractive reactants for several reasons. Under proper conditions the reaction is electrochemically reversible. Both are molten at 115°C, and if sodium is added to a fixed amount of sulfur, a high specific energy can be obtained before the melting point of the reaction product exceeds 300°C. Both sodium and sulfur are plentiful and inexpensive and can be contained at 300°C in vessels made of common materials such as stainless steel and aluminum. The highest pressure encountered is the vapor pressure of pure sulfur, about 60 millimeters of mercury at 300°C.

Figure 2 shows the open-circuit potential of the sodium-sulfur system as a function of composition. The voltage remains constant at 2.08 until a composition corresponding to sodium penta-sulfide is reached. It then drops almost linearly to 1.76 at a composition corresponding to sodium trisulfide. The temperature of operation is dictated by the melting point of the product, and the constraints thus imposed are illustrated in Figure 3, which is the phase diagram for the system Na_2S-S (Pearson and Robinson, 1930). At the operating temperature of 300°C, solid will begin to separate out at about the composition Na_2S_3. This composition is the maximum contemplated degree of reaction, or the discharged state. On the right-hand side of the diagram, the sulfur side, the system is two phase at 300°C, liquid sulfur and liquid sodium pentasulfide.

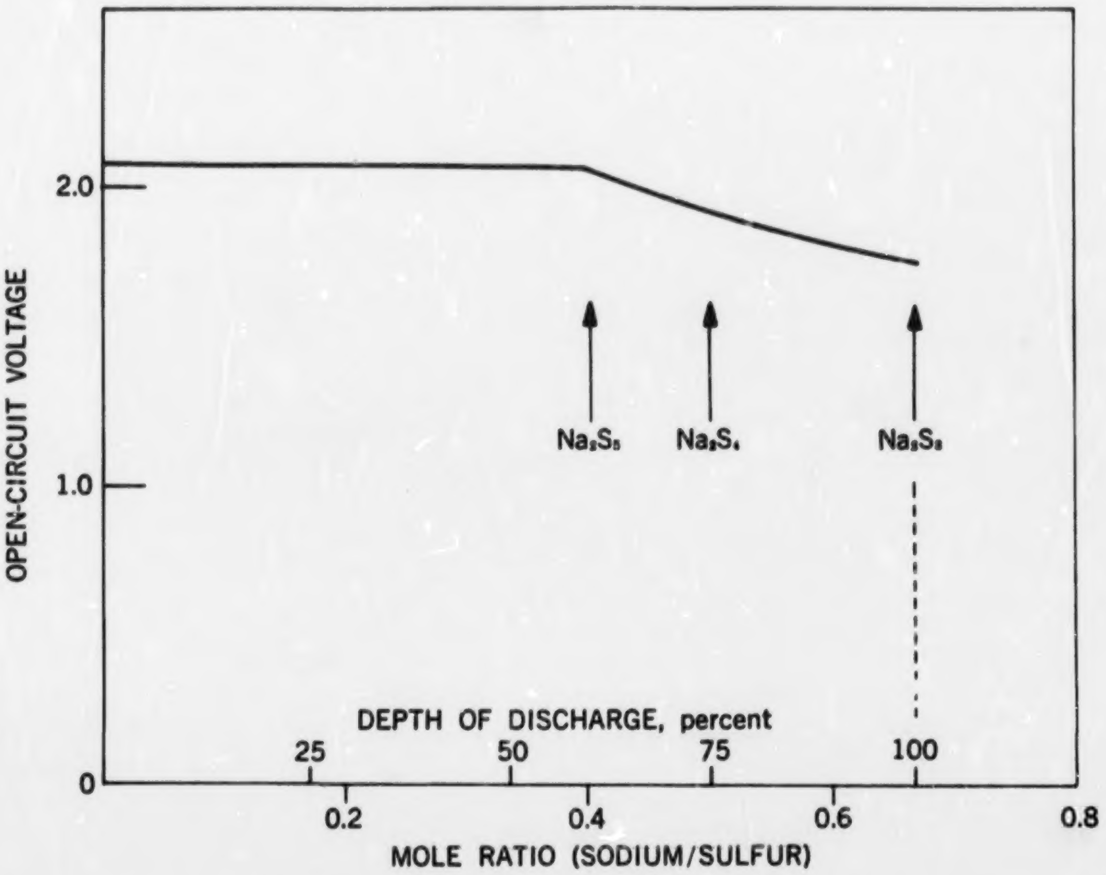


Figure 2. Open-circuit voltage of sodium-sulfur cell vs. state of discharge.

CONDUCTING CERAMIC MEMBRANE

The heart of this battery concept is the ionically conducting solid electrolyte around which most of the research centered. The original materials examined for use as solid sodium ion conductors were glasses, principally those in the soda-alumina-silica system. The requirements for a solid electrolyte material separating sodium and sulfur are stringent. Good conductivity, chemical corrosion resistance to the reactants, usable strength, and impermeability are essential properties.

No one glass composition was found perfectly satisfactory, but in the course of investigation a crystalline material known as beta-alumina was encountered and recognized as having the sought-after properties. Beta-alumina is not a form of Al_2O_3, but is a sodium

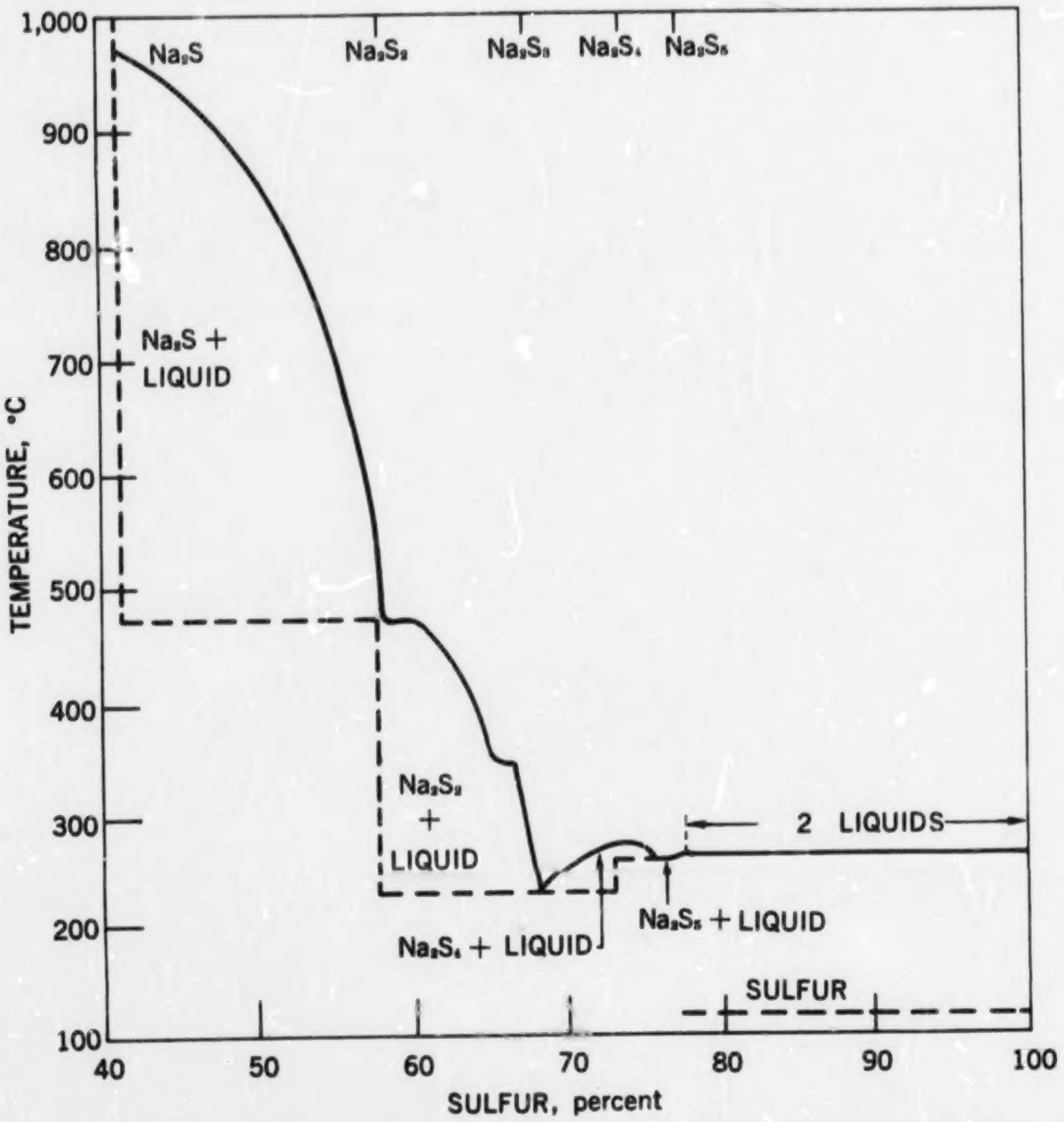


Figure 3. Phase diagram of the system Na_2S-S (after Pearson and Robinson).

aluminate with the generally accepted formula $Na_2O \cdot 11Al_2O_3$. This is not a new material, but its high ionic conductivity has not been previously recognized. The structure of beta-alumina (Beavers and Ross, 1937) is known and is shown in Figure 4. It is a layer structure in which sodium ions are found in relatively open planes together with bridging oxygen ions that have the effect of providing a spacing that results in nearly optimum mobility in this structure for a monovalent ion the size of sodium. The oxygen ion "prop" is what distinguishes beta-alumina from other materials with a layer structure such as mica. Application of theories and techniques from solid-state and crystal chemistry resulted in producing proprietary derivatives of beta-alumina that can be made into highly conductive, stable, impervious shapes by conventional ceramic-forming procedures. The electrical resistivity of the formed polycrystalline ceramic is shown in Figure 5. At 300°C the resistivity is about 5 ohm-centimeters, which is comparable to the values for molten salts and aqueous sulfuric acid and potassium hydroxide.

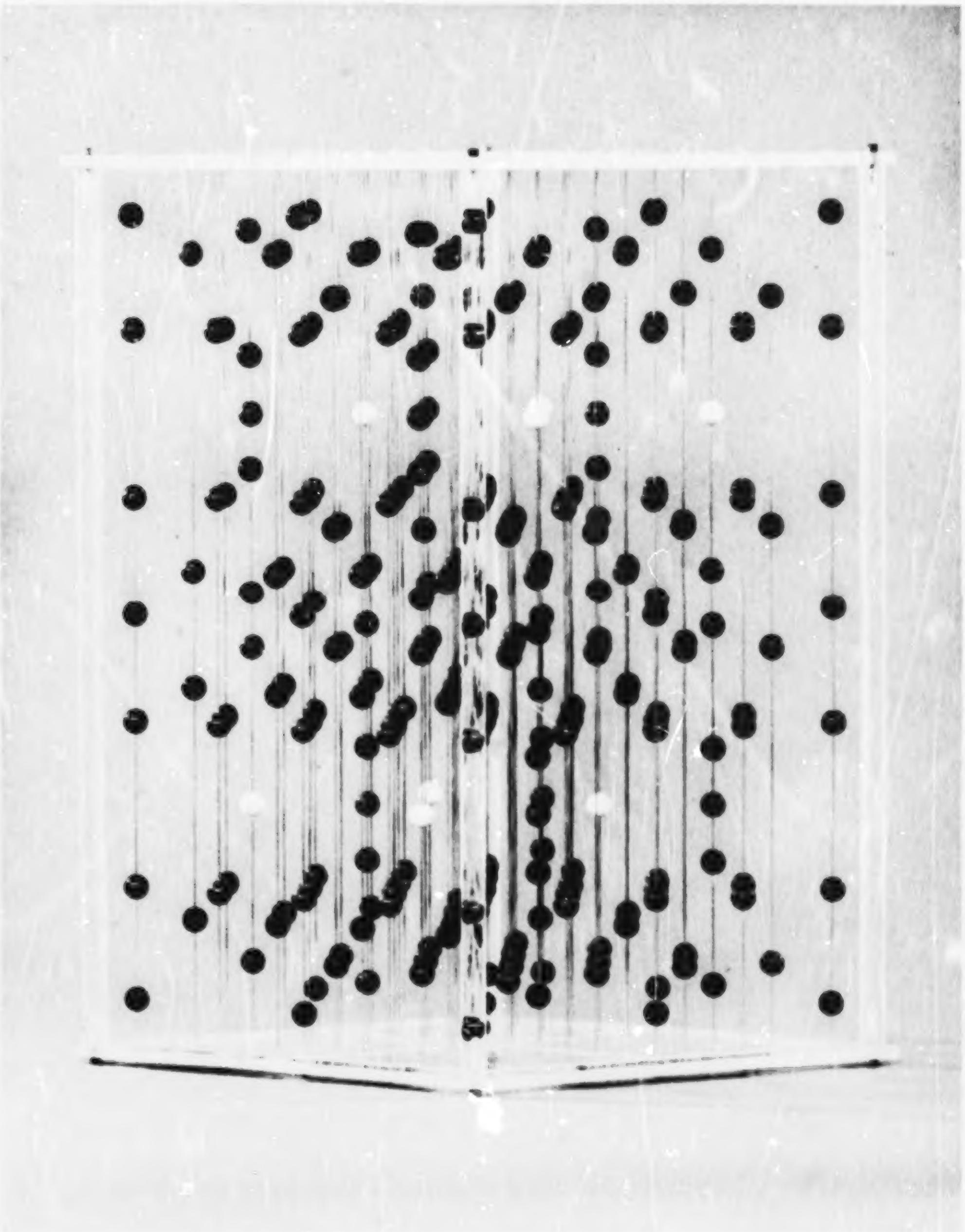


Figure 4. The structure of beta-alumina (after Beavers and Ross). White balls are sodium.

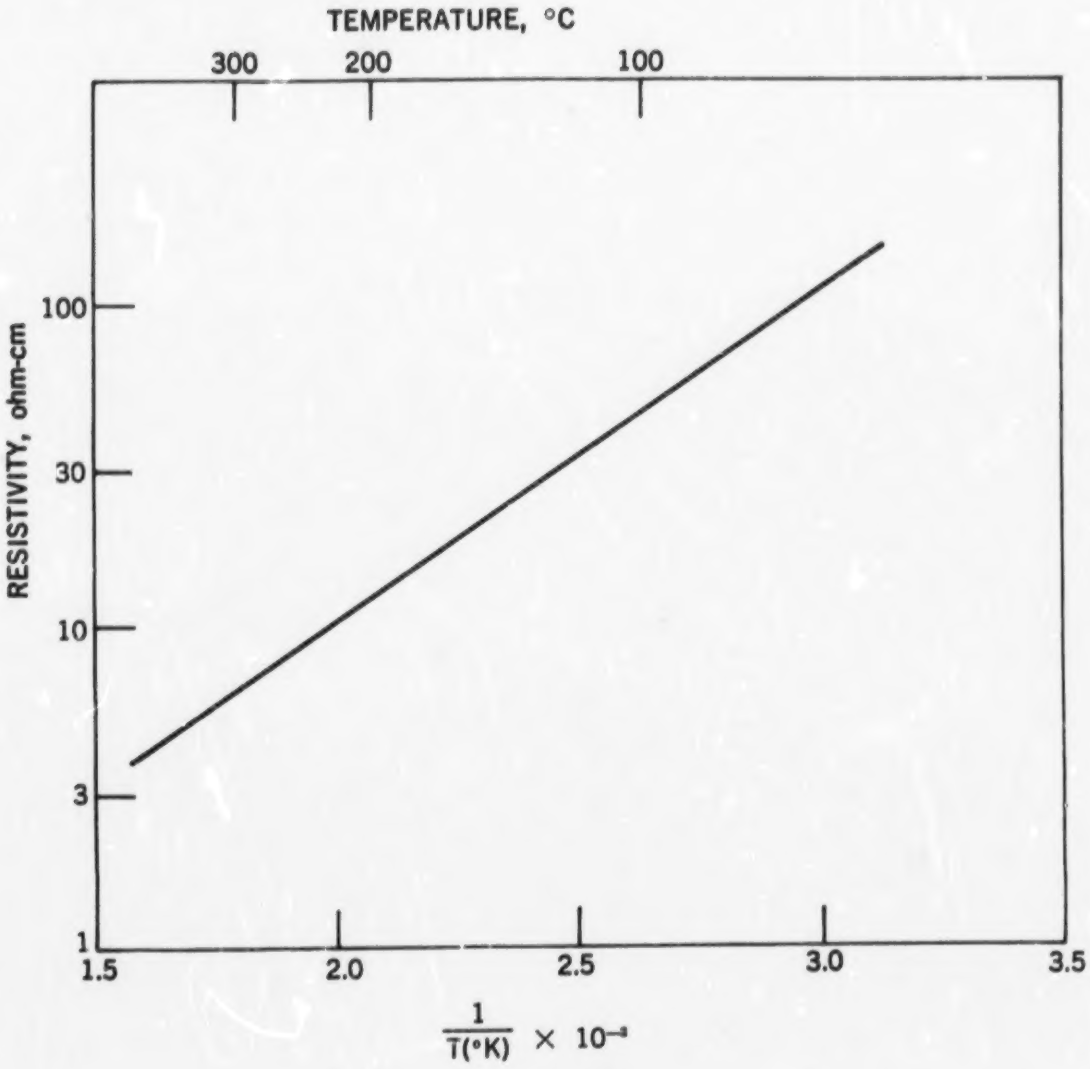
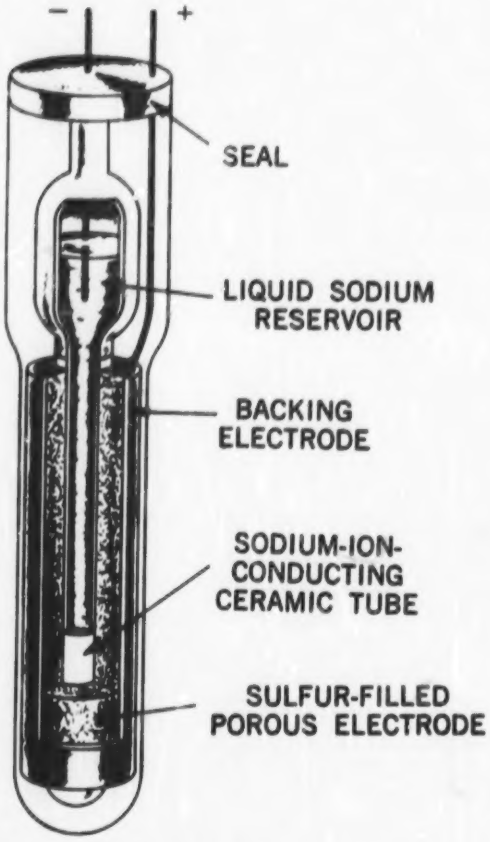


Figure 5. Electrical resistivity vs. temperature of ion-conducting ceramic.

LABORATORY SCALE CELL

Ceramic membranes in the form of thin-walled tubes have been used to construct sealed cells like that shown in Figure 6. Sodium is contained in a reservoir sealed to the top of the ceramic tube, the other end of which is closed. Surrounding the ceramic tube is sulfur contained in a porous graphite electrode that makes contact with the ceramic and a backing electrode. Typical charge-discharge curves for a cell of this type with a 3 millimeter thick layer of sulfur and 0.8-millimeter ceramic wall thickness are shown in Figure 7. Of note are the high current densities, computed from surface area of ceramic, that can be achieved at terminal voltages consistent with only pure ohmic resistance of ceramic, sodium sulfides, and porous electrode. The data contain little indication of polarization from charge transfer or diffusion-controlled electrode reactions.

Operating experience has confirmed the expected advantages of this battery concept over other systems. Being liquid, the reactants are regenerated to the same physical form during repeated charge-discharge cycling, obviating a source of limited cycle life as in cells with solid reactants. The cell reaction is simple; it has no gaseous reactants or products and no known side reactions or mechanisms for self discharge. No auxiliary equipment is required except thermal insulation.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+
SEAL
LIQUID SODIUM RESERVOIR
BACKING ELECTRODE
SODIUM-ION-CONDUCTING CERAMIC TUBE
SULFUR-FILLED POROUS ELECTRODE

Figure 6. The construction of a small sodium-sulfur cell.

PROJECTED SCALE-UP

This battery is still in the advanced laboratory stage, and current emphasis is on obtaining data necessary for proper design of larger units. No basic barrier to its larger scale development is known at present, and although problems associated with materials of construction, configuration, reliability and the like remain to be faced, it is anticipated that these can be solved.

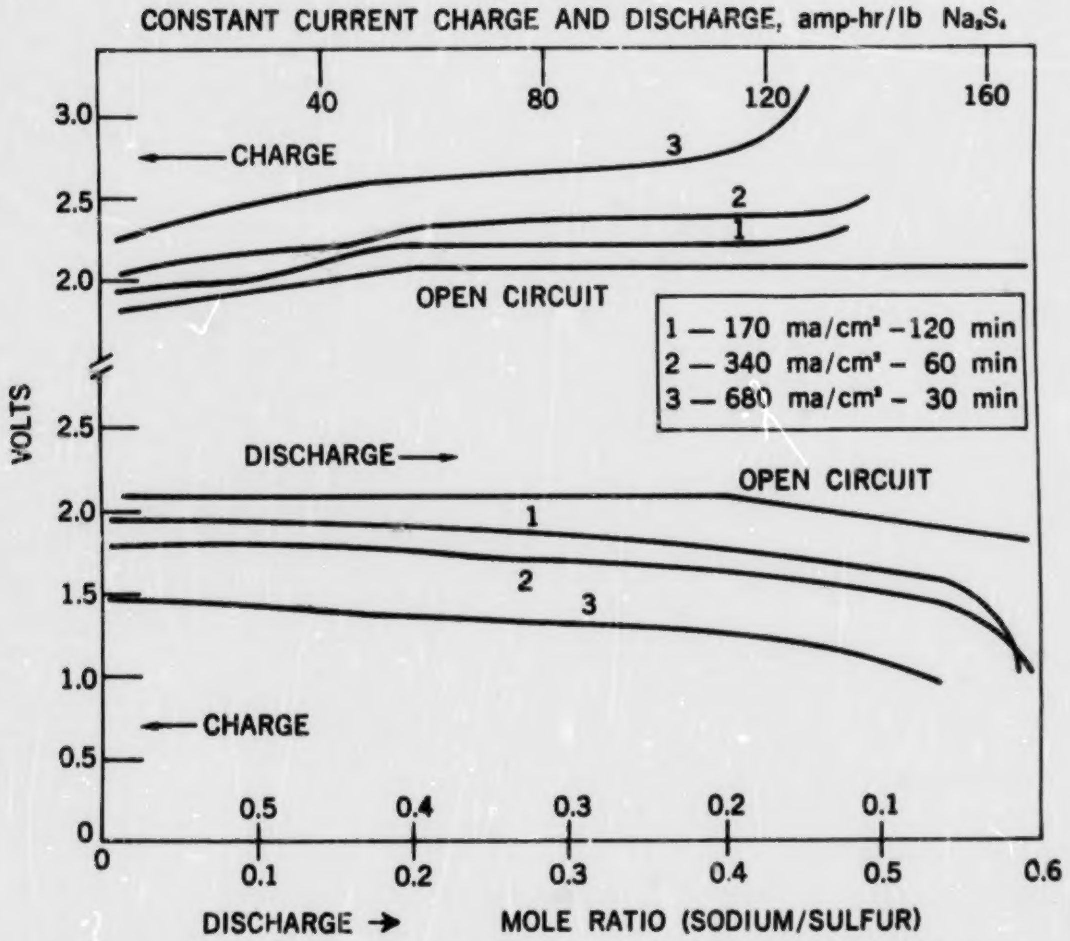

Figure 7. Terminal voltage vs. state of discharge for steady discharge and charge currents of 170, 340, and 680 milliamperes per square centimeter of ceramic membrane.

When the laboratory data are projected to the design of larger size units, one result is the proposed cell shown in Figure 8. The specifications for such a unit are given in Table 1. The rated energy density, 148 watt-hours per pound, represents about 45 percent of the theoretical 346 watt-hours per pound. These numbers are compared in Table 2 with those for several conventional batteries.

At the present time it is expected that a battery of the size shown in Figure 8 will be in operation in a year and one in the 20- to 40-kilowatt range in 2 years. It will certainly be several years before any appreciable number of these batteries will be available for the purpose of exploring other applications. Although the primary interest, and immediate focus, is in the use of this battery system for motor vehicle propulsion, it is anticipated that it will ultimately have many other applications, both civilian and military. Since it operates at elevated temperatures, its usefulness in areas such as miniature batteries and small portable power sources is limited, except for very special applications. In sizes of a kilowatt or more, the temperature problem diminishes considerably in magnitude, and in some instances the higher operational temperature may even be an advantage. A few of the areas in which it may have applicability include: electric lawnmowers, garden tractors, farm tractors, submarines, electric railway cars, and materials handling equipment.

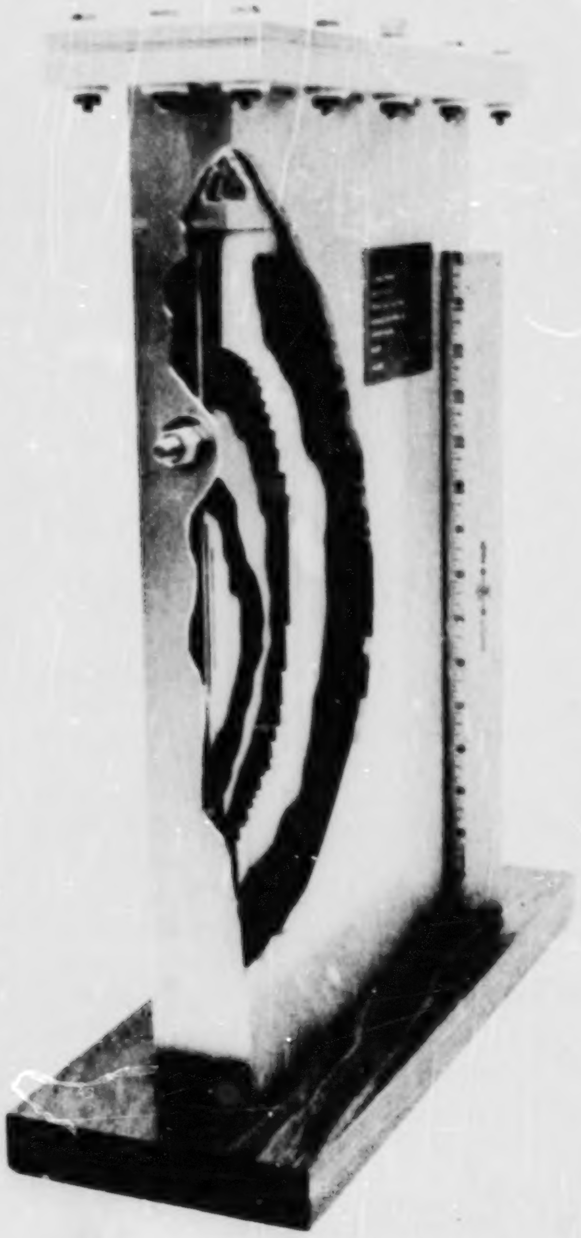

Figure 8. Mock-up of a proposed 2-kilowatt cell, showing planar array of sodium-filled ceramic tubes.

Table 1. SPECIFICATIONS OF PROPOSED CELL

Average power, kw	2
Maximum power, kw	4
Open circuit voltage	2.08
Average discharge voltage	1.75
Ampere-hours	1,850
Weight, lb	22
Volume, in.^{3}	400

Table 2. COMPARISON OF BATTERY SYSTEMS

	Energy Density, w-hr/lb (slow discharge, 5 hr)	Weight/power ratio, lb/kw (rapid discharge, ¼ hr)
Lead-acid	10	31
Nickel-cadmium	14	25
Silver-cadmium	24	15.5
Silver-zinc	50	6.5
Ford sodium-sulfur	150	10

APPLICATION IN VEHICLES

It is premature to do anything but speculate on what this battery could mean for an electric car since there are many problems to be solved, not only with the battery, but with motors and controls, before it can become a practical reality. It is nevertheless possible, and useful, to make a tentative calculation of what might be achieved. For example, 350 pounds of sodium-sulfur battery in a 1350-pound commuter car should allow it to cruise at 40 miles an hour for 200-300 miles, at 60 miles an hour for 125 to 200 miles, and have a top speed of about 70 miles an hour. Such a car's performance should be adequate in an urban-suburban environment.

The chief disadvantage of this battery, even for motive power use, is the high temperature of operation. The battery is in-operative at room temperature, so a cold start is impossible, unless auxiliary heating is used. A large battery has a considerable heat capacity, and the time required to bring it up to operating temperature with any practical auxiliary system would probably be unacceptable except for very infrequent occasions. However, the solution to this problem is to keep the battery hot all the time. This should present no problem for an urban-suburban vehicle that will be garaged almost every night for overnight charging anyway. Indeed this has some advantages since the car would require no warmup period and would be ready for instant starting at all times. There is no problem during operation, since internal power dissipation in the battery is more than sufficient to keep it hot. Indeed, cooling will undoubtedly be necessary. There will be, of course, occasions when the car will not have access to charging facilities, perhaps for several days or even a week or more, and here it should be very simple to arrange it so the battery uses its own energy to keep itself hot for such periods of time and still have enough left over for operation of the car. The minimum charging time for the battery might be as short as a half hour, depending on the cooling facilities.

Clearly, the question of safety must be faced. There is little danger arising from an internal breakage in the battery with a consequent mixing of the reactants. As has been mentioned, there are no gaseous products involved at all, and under certain circumstances, direct reaction between sodium and sulfur is self-attenuating because the product, sodium sulfide, provides a barrier between the liquid reactants. The one thing that must be prevented, of course, is the escape of hot sodium and sulfur from the container in the event of an accident, and proper packaging is the answer to this.

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LITHIUM NICKEL-HALIDE BATTERIES

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INTRODUCTION

The battery industry is partial to a term called the theoretical energy density. This is calculated by taking stoichiometric amounts of the anode and cathode materials in their charged state. Then we look up the Gibbs free energy for the reactions and calculate the theoretical voltage of the system. Next, we use both the free energies and the equivalent weights to obtain the theoretical watt-hours per pound. Unless the electrolyte is required in balancing the chemical reaction, it will not be used in the weight calculations. To have a practical working battery, a case is needed, and so are grids to hold the active materials, tabs to connect plates to terminals, and a separator that prevents electronic short circuits while holding the electrolyte that supplies the electrochemical conductivity. The weight of these items cannot be readily calculated, but practical batteries have watt-hour per pound ratios that are about 20 percent of the theoretical values. So let us consider the theoretical value as a Figure of Merit for comparison purposes, and bear in mind that 20 percent of these numbers are realistic.

The present battery systems have been pushed rather far, and it is difficult to visualize how the watt-hour per pound ratios can be increased much more. Significant increases in energy-to-weight ratios must come from systems that have not previously been reduced to practice as batteries. The first step is a tabulation of materials that may serve as anodes and materials that may serve as cathodes. Lithium is the first metal encountered in the table of electromotive force, and it is the lightest metal. Between its half-cell potential and equivalent weight, coupling it with almost any cathode makes an attractive system. Lithium supplies the energy, and the cathode supplies the weight.

Because lithium is so energetic, it is, as a consequence, extremely reactive with water, oxygen, hydrogen, and even organic liquids that contain active hydrogen. As an example of the latter, lithium reacts with ethyl alcohol to form lithium alcoholate, a reaction that proceeds with the release of hydrogen gas.

This paper is essentially a progress report on our efforts to develop a battery using lithium as the anode and the nickel halide as the cathode. The fluoride system has a theoretical energy-to-weight ratio of 620 watt-hours per pound, which I now feel obliged to divide by 5 to obtain 120, and the chloride system has a theoretical value of 437 watt-hours per pound, a fifth of which is 87.

ELECTROLYTE

Since lithium is so reactive, the first thing one must do is find a liquid medium with which it is not spontaneously reactive. But the list of required criteria is quite long. The electrolyte consists of a solvent and at least one solute. If only one solute is used, then it must supply the ions that migrate under the electric field, and these ions must also participate in the charge transfer steps at the electrode and electrolyte interface. If two solutes are used, the one that does not participate in the charge transfer process at the interface is called the supporting electrolyte. The supporting electrolyte merely carries the current in the electric field. The fraction of the current carried by each kind of ion is its transport number.

In Table 1 are listed some non-aqueous solvents of interest. Five of these contain a double-bonded oxygen, and the sixth, acetonitrile, is also an unsaturated compound containing a triple bond-nitrogen. The dielectric constants for the double-bond-oxygen compounds range from 38 to 64 and that for acetonitrile is 38.

Solvent	Viscosity, centipoises	Melting point, °C	Boiling point, °C	Diaelectric constant	Specific conductivity, millimhos/cm			
					LiCl	$AlCl_3$	KPF_6	$NaPF_6$
Dimethyl sulfoxide	1.98	18.45	189	46.7	9.91	0.37	10.2	10
Nitromethane	0.62	—29	101	38	31.8	33.3	5.91	12.3
σ-Butyrolactone	1.75	—44	206	39.1	0.008	4.4	—	13.2
N-methyl-2-pyrrolidone	1.65	—24	202	45.4	0.16	—	—	8.2
Acetonitrile	0.345	—41	82	38.3	—	—	12.0	43.0
Propylene carbonate	2.53	—49	241	64.4	0.34	4.5	7.2	7.5

The boiling points and melting points of these solvents are important because they define the temperature range over which the battery may operate. This temperature range is widened, however, by the freezing point depression and the boiling point elevation that come about upon dissolution of salts.

The solute must dissolve in the solvent, naturally, and it must ionize. The goal here is to have a high conductivity. There must be an anion that is the same as the anion in the electroactive species in the cell. As mentioned before, these requirements may be met by using two solutes instead of one.

Candidate electrolytes were originally tested for compatibility with the electrode materials. These tests were run by placing the electrode and the electrolyte in sealed Kel-F containers for periods up to 6 months. Two electrolytes have done well in these posts, thus far — propylene carbonate and dimethyl sulfoxide. The solute was potassium hexafluorophosphate for both. The concentrations of solute taken at the maximum conductivity are:

Propylene carbonate	90g/l	KPF_6	7.2×10^{-3}	mho/cm
DMSO	190g/l	KPF_6	11.6×10^{-3}	mho/cm

Dimethyl sulfoxide is also a solvent for nickel chloride and thus cannot be used because there will be a self-discharge process at the lithium electrode. When the propylene carbonate KPF_6 is used with this chloride system, LiCl is added to the electrolyte, a specific example of the use of two solutes.

LITHIUM ANODE ELECTRODE

When an electrode is fabricated, it must possess electrical conductivity in both the oxidized and reduced states. This statement is equally true for both anodes and cathodes. Many of the oxidized materials commonly used are found to be semiconductors. Other electrodes may have only thin films, or there may be an intimate mixture; the graphite and flake nickel in Edison storage batteries is an example of such mixture.

A pasted lithium electrode was developed with the paste consisting of a mixture of powdered lithium and conductive granular carbon, a binder and a vehicle.

The paste was spread onto the substrate in a dry box. It was then pressed, after which the solvent was removed by heating in a vacuum oven and the vehicle leached out.

The electrical capability of an electrode is shown by a polarization diagram as depicted in Figure 1.

The electrode was discharged against a counter electrode. A reference electrode, mercury/mercuric chloride, was used to monitor the voltage of the lithium electrode, while a motorized potentiometer varied the current through the electrode. The electrodes used had an area of 10 square centimeters. The charge region is to the right of zero current, and the discharge behavior is shown on the left of the origin. The maximum current density shown corresponds to 65 milliamperes per square inch. The attendant polarization was 0.1 volt. In a conventional nickel-cadmium battery, 65 milliamperes per square inch is equal to about the 1-hour discharge rate.

The lithium anode is far from the limiting factor in this cell, with regard to performance, and we are not attempting any further improvements in performance at this time. Our concentration of effort is on the cathode materials.

NICKEL HALIDE CATHODE ELECTRODE

A survey of cathode materials to be used with a lithium anode reveals several attractive anion materials. A few selected materials, their voltage as a lithium cell, and their total energy content in watt-hours per pound, are listed in Table 2.

Table 2. THEORETICAL CELL POTENTIAL AND ENERGY CONTENT OF SELECTED Li — CATHODE COUPLES

Cathode reactant	Product	Li Cell potential, volts	Energy content, w-hr/lb
F_2	F^-	6.05	2740
Cl_2	Cl^-	4.02	1142
CuF_2	$Cu + 2F^-$	3.55	749
$CuCl_2$	$Cu + 2\ Cl^-$	3.06	505
NiF_2	$Ni + 2F^-$	2.83	620
$NiCl_2$	$Ni + 2\ Cl^-$	2.57	437

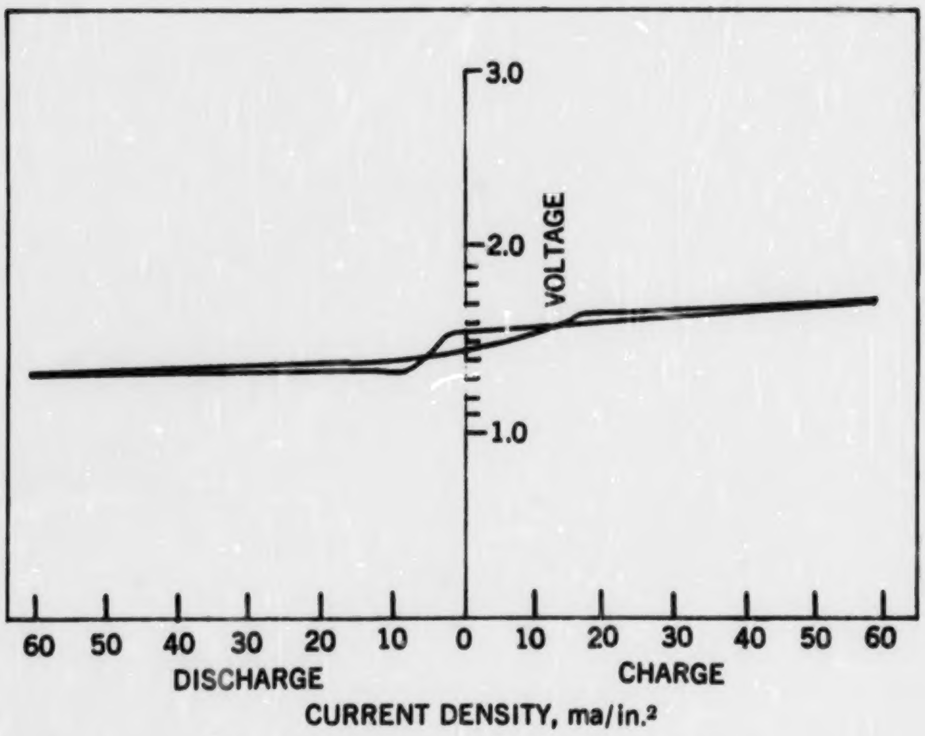

Figure 1. Polarization diagram of a lithium anode.

For work on a rechargeable cell the nickel halides were selected as cathodes. The nickel halide electrodes proved to be more limiting than either the lithium electrode or the electrolyte. Perhaps the greatest problem is that the halides of nickel are not good conductors.

At the beginning of the program we were ready to drop NiF_2 because anything more than an electrometer brought the voltage of a cell to zero rather quickly.

The nickel chloride electrode was more favorable, and a pasted electrode similiar to the lithium electrode was developed. The initial current densities achieveable were low, however. Investigations were directed at doping the nickel halide, improving the conductive diluents, and improving the fabricating techniques to get higher current densities. The techniques developed when applied to the NiF_2 electrode made an attractive electrode. A current density of 18 milliamperes per square inch, equivalent to the 5-hour rate of discharge, has been achieved.

CELLS

Cells have been constructed using the pasted lithium and nickel-fluoride formulations. The active area for 20 ampere-hour cells is 45 square centimeters per electrode side, and eight lithium electrodes and nine nickel-fluoride electrodes were incorporated into each cell. The separator was a 60 percent porous sheet of non-woven polypropylene. The electrolyte was propylene carbonate with KPF_6 added. These cells have the energy content of two nickel-cadmium cells that weigh 4 pounds compared to the 0.5 pound per lithium cell.

The contribution of electrolyte to the cell's internal resistance was calculated to be 0.027 ohm. Pulse data such as shown in Figure 2 show an internal resistance of 0.35 ohm. The cell pulsed at 2 amperes shows a terminal voltage of 2.5 volts. At 4 amperes, the C/5 rate cell voltage is 2.0 volts.

Several small laboratory cells were built and cycled unsealed in an argon atmosphere glove box. They were discharged at the C/10 rate and recharged at 3.6 volts. Figure 3 shows cycle data after 2 and 20 cycles.

DISCUSSION

The feasibility of the lithium-nickel halide battery has been demonstrated. As a low-rate cell or as a primary cell, its performance is very attractive. Recent development has been directed at achieving higher rates of discharge suitable for electric vehicles. At the C/5 rate of discharge, which has been realized, the battery can provide power for cruising of a vehicle and its energy density of 100 watt-hours per pound provides an attractive mileage range. Its present limitation is its power density of 50 pounds per kilowatt, which requires too large a battery to provide acceleration peaks.

Bipolar nickel-cadmium batteries have been developed in our laboratories. Because of their unique geometry and construction, these batteries have a weight to power ratio of 3 pounds per kilowatt for short periods of time — of the order of minutes.

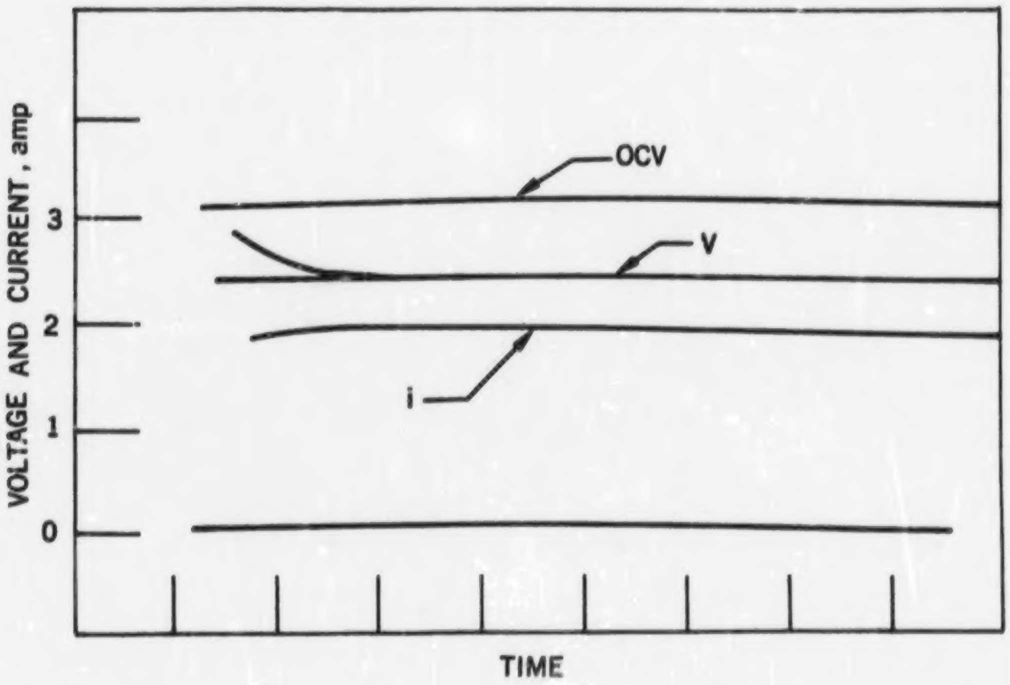

Figure 2. Current voltage trace for 20-ampere-hour lithium cell at 18 milliamperes per square inch.

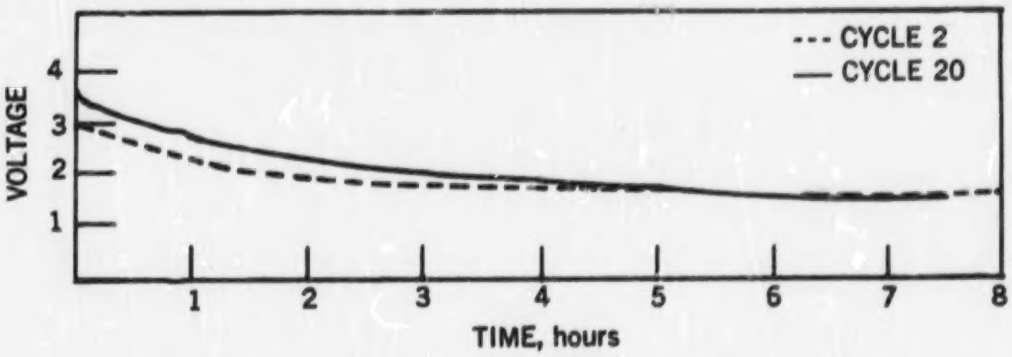

Figure 3. Discharge data for lithium cell.

A small bipolar nickel-cadmium booster battery coupled in parallel with the lithium battery can provide the necessary peak power. It can be small compared to the lithium battery, since the duration of acceleration peak loads is short, and during cruising, the bipolar battery can be recharged in minutes from the main battery. Bipolar nickel-cadmium battery technology is well-advanced.

Let us look at the application of the lithium battery to electric vehicle propulsion. A vehicle weighing about 3,000 pounds requires about 5 horsepower to cruise on level road at 30 mph. For grades and acceleration peaks, it would require up to 15 horsepower. If we assume approximately a 75 percent conversion of electrical power to mechanical power, then the same number of kilowatts can be used as indicated above for horsepower. For cruising at 5 kilowatts a lithium battery with a weight-to-power capability of 50 pounds per kilowatt would have to weight at least 250 pounds. At 100 watt-hours per pound, it would be capable of 5 hours of operation, which at 30 mph is 150 miles. To provide the 15-kilowatt peaks would require about 45 pounds of bipolar nickel-cadmium battery at 3 pounds per kilowatt. Since 5 kilowatts would still be coming from the lithium battery, 45 pounds allows some margin of safety and the peak would be available for several minutes if necessary.

The non-aqueous lithium-nickel halide battery coupled with a bipolar nickel-cadmium booster has attractive features for vehicular propulsion. Further work is in progress to optimize the lithium system and to evaluate its capabilities.

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A STATE-OF-THE-ART AUTOMOTIVE FUEL CELL

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INTRODUCTION

Interest in the electric automobile has recently been widely revived. In most of the articles published on the subject, the lead-acid battery is examined as a source of electrical energy for the vehicle. But all agree that the lead-acid battery is marginal at best, its basic shortcoming being the limited range it affords the vehicle at any reasonable battery weight. Attention has naturally turned to supplying electrical energy by other means, and among these the fuel cell is almost invariably proposed.

Little factual data exist on large, air-breathing fuel cells suitable for automotive use. This paper describes one existing fuel-cell automotive power plant to allow a comparison with other sources of energy, such as the lead-acid battery.

THE 5-KILOWATT FUEL-CELL MODULE

Monsanto Research Corporation in cooperation with the U. S. Army Engineer Research and Development Laboratories has developed a hydrazine-air fuel cell module that when used in multiples provides power to drive an M-37 Army truck. The fuel cell module is designed so that fuel dissolved in the electrolyte can be circulated through the anode compartments. The circulation rate is high enough that the electrochemical fuel consumption hardly changes the fuel concentration, even at high load. This circulating liquid also provides the means for cooling the fuel cell. The module consists of 140 cells spatially arranged so that anode faces anode (as opposed to a bi-polar scheme). The anodes are connected electrically in parallel by a metallic grid; the current is collected and brought to the edge of the electrode. Similarly, adjacent cathodes face each other, but in operation they are at different potentials, typically being 0.78 volt apart. An insulating plastic grid is incorporated in the cathode compartment. As with the anodes, the cathode current is collected and brought to the edge of the electrode. External electrical connections are made so that each pair of cells (one cell being one cathode and one anode) is in series with the next, and appropriate cathodes are in parallel. Figure 1 shows a schematic diagram of the arrangement and the external electrical connections. The module consists of two side-by-side decks of 70 cells each, connected in parallel electrically and clamped between common end plates. At rated load each cell is designed to deliver 0.78 volt. Since each pair of cells is wired in parallel, the rated voltage of the module is:

$$\frac{70}{2} \text{ x } (0.78) = 27.3 \text{ volts}$$

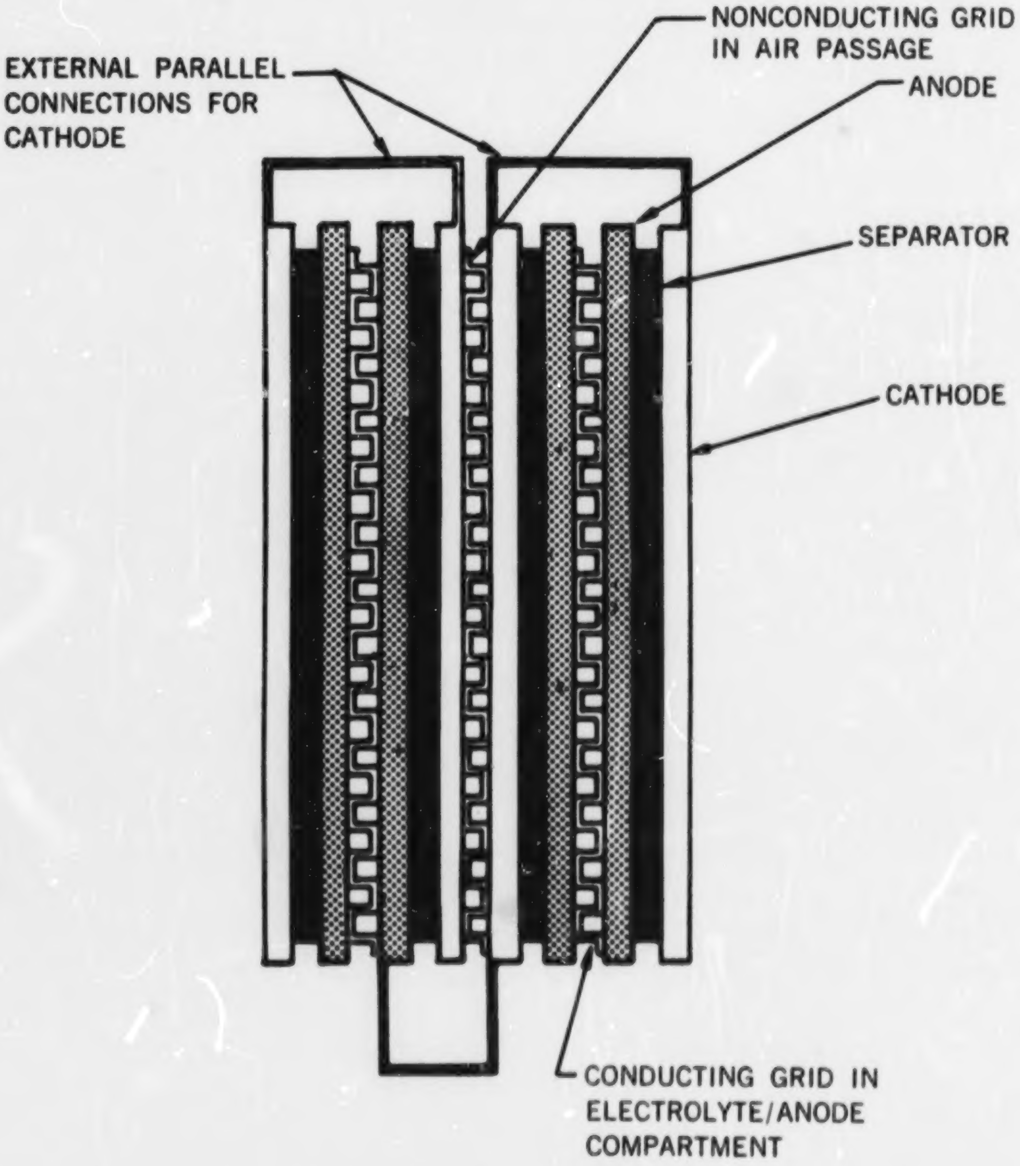
NONCONDUCTING GRID IN AIR PASSAGE
EXTERNAL PARALLEL CONNECTIONS FOR CATHODE
ANODE
SEPARATOR
CATHODE
CONDUCTING GRID IN ELECTROLYTE/ANODE COMPARTMENT

Figure 1. Hydrazine-air fuel cell module with external connections.

Each electrode has an active area of 62 square inches and is rated at 44.5 amperes at a rated current density of 103 amperes per square foot. Two cells in parallel deliver 89 amperes, which is the current carried by each deck. Twin decks in parallel carry 178 amperes at 28 volts and yield a 5-kilowatt rating. The module is shaped like a box with overall dimensions of 9 by 9 by 22½ inches and a weight of 95 pounds with electrolyte (Figure 2). At the 5-kilowatt rating, the power density is 4.38 kilowatts per cubic foot, and the specific weight is 19 pounds per kilowatt. Under design conditions about 700 watt-hours are generated per pound of hydrazine monhydrate (about 90% of ideal). Figure 3 shows the average single-cell polarization curve, based on module tests.

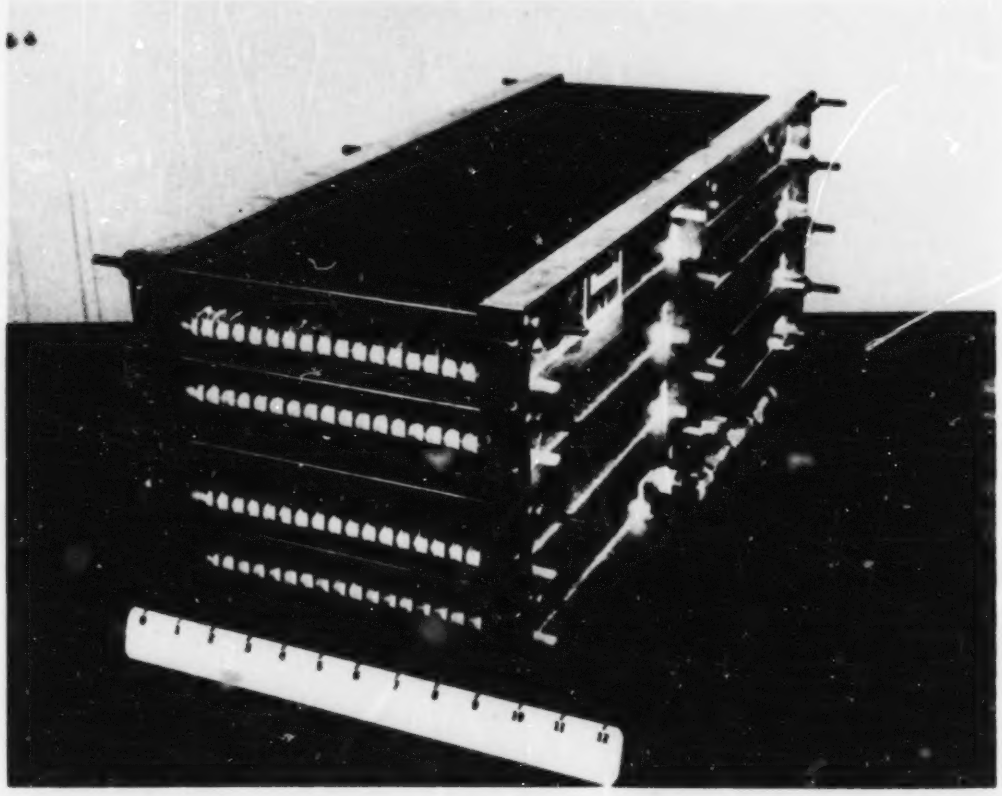

Figure 2. Five-kilowatt hydrazine-air fuel cell module.

At rated power the average single-cell voltage is 0.78 volt, which is about 48 percent of the thermodynamically reversible voltage for the hydrazine/oxygen couple. Thermal efficiency at this condition is about 50 percent, based on the higher heating value of hydrazine.

THE POWER PLANT IN THE M-37 ARMY TRUCK

The power plant consists of three major elements: the fuel cell, with its controls and accessories; the electric motor; and the motor

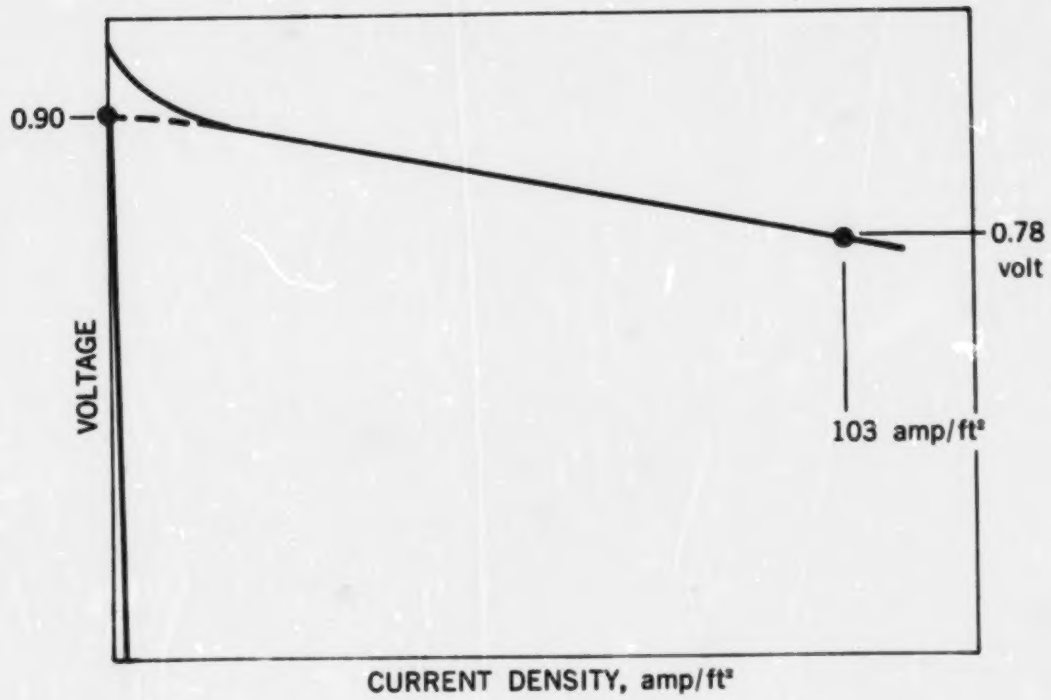

Figure 3. Average single-cell polarization curve.

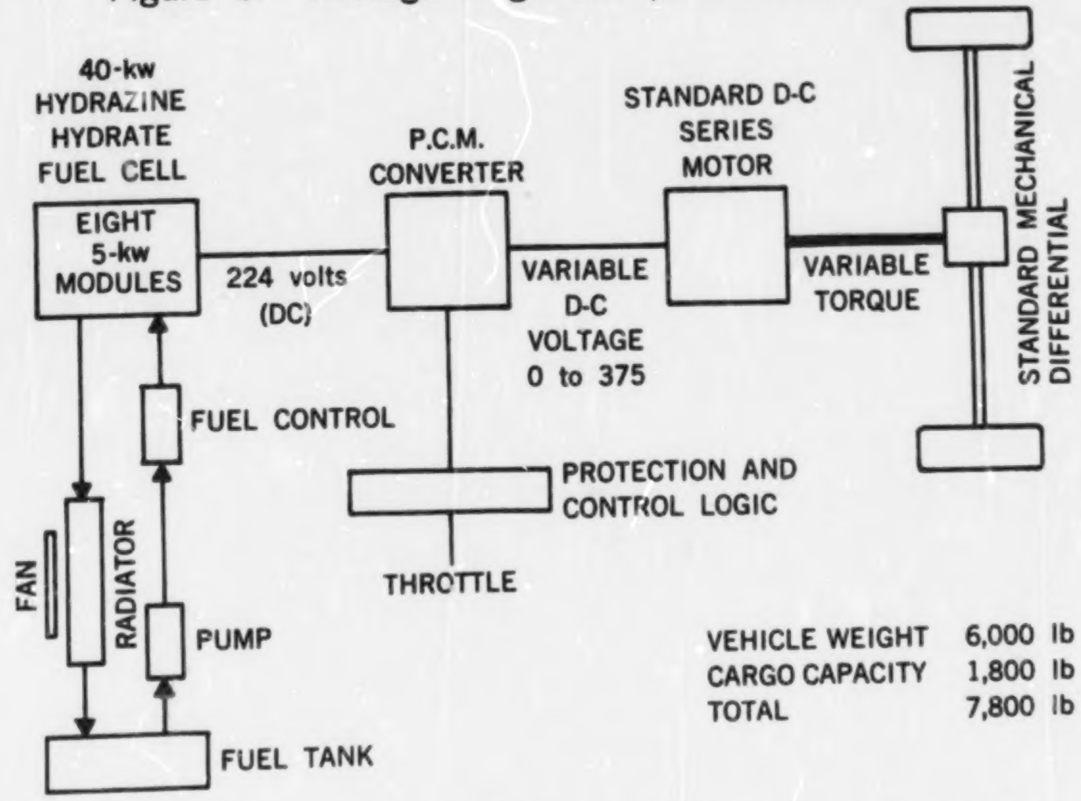
40-kw
HYDRAZINE
HYDRATE
FUEL CELL
EIGHT
5-kw
MODULES
224 volts
(DC)
P.C.M.
CONVERTER
VARIABLE
D-C
VOLTAGE
0 to 375
STANDARD D-C
SERIES
MOTOR
VARIABLE
TORQUE
STANDARD MECHANICAL
DIFFERENTIAL
FUEL CONTROL
PROTECTION AND
CONTROL LOGIC
THROTTLE
FAN
RADIATOR
PUMP
FUEL TANK
VEHICLE WEIGHT 6,000 lb
CARGO CAPACITY 1,800 lb
TOTAL 7,800 lb

Figure 4. The power plant for the M-37 army truck.

and vehicle control system. Figure 4 shows a schematic block diagram of the power plant.

At present, the fuel cell is made up of four of the 5-kilowatt modules described above with a full load rating of 20 kilowatts. The modules are mounted on a bedpost frame, which in turn is shock-mounted on the truck chassis under the hood (Figure 5). Although four modules have been used thus far, space for eight has been provided and much of the system is designed for eight-module power of 40 kilowatts. The modules are connected in series, giving a full-load voltage of over 100 volts for the four-module system and over 200 volts for the eight.

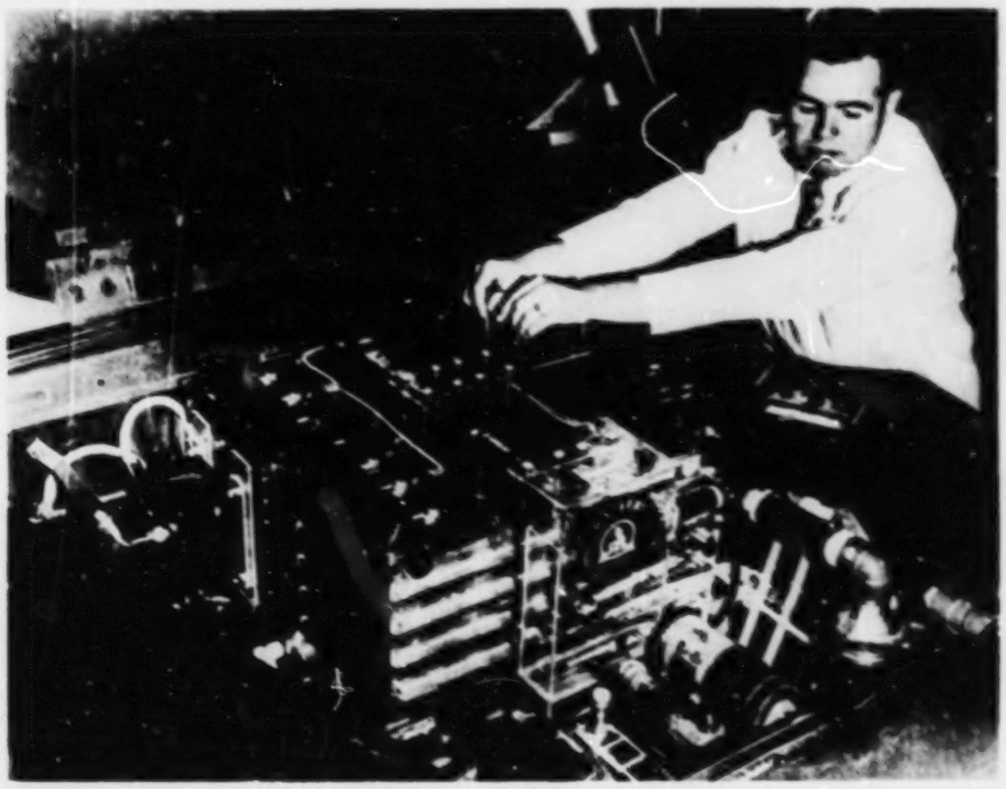

Figure 5. Four 5-kw hydrazine-air fuel cell modules installed as power plant for M-37 truck.

The installed fuel-cell-plus-accessory weight is 525 pounds for four modules and 915 pounds for eight. Four modules weigh about 340 pounds dry. The weight of electrolyte required to charge the system is 100 pounds. The radiator, which is an air-to-electrolyte heat exchanger, weighs about 45 pounds. The latter is a finned, tube radiator, very similar to those found on many American cars. To enhance ram-air cooling, an electric-motor-driven fan is provided. Fuel is supplied intermittently by a pump to the electrolyte tank. The "on" versus "off" time of the fuel flow determines the average quantity of fuel delivered. This in turn is regulated by the voltage on the terminals of one of the modules. Furthermore, the control voltage is a function of current and is highest at no load. This ensures good transient performance following the sudden application of a large load despite the inevitable dip in voltage. Parasitic power drain for the 40-kilowatt system is about 600 watts.

A direct-current traction motor is mounted under the truck body forward of the differential that it drives. The motor is rated at a stall torque of 625 foot-pounds; starting current is 525 amperes. The latter is a short-time rating only. The motor weighs 700 pounds, and is being used at present only because of its availability. To do the same job, a motor weighing only 300 pounds has been ordered and will very shortly be installed in the truck.

The controller for the motor is mounted under the driver's seat. The basic purpose of the controller is to convert the voltage and current output of the fuel cell to that required by the motor. The controller ensures that neither the operator demand nor motor load shall exceed the power capability of the fuel cell. Figure 6a shows how motor current, voltage, and power very as a function of vehicle velocity following a full-throttle start from a standstill. Figure 6b shows the fuel cell voltage and current on the same scale. In the span marked A the controller limits the current to the motor to 525 amperes. Since the short-circuit current of the fuel cell is about 2,500 amperes, protection is clearly required. As the vehicle and the motor pick up speed, motor voltage is increased to maintain the current limit. At the end of span A, the motor power is equal to 40 kilowatts, which is equal to the peak fuel cell power (for the eight-module installation). During the span marked B the vehicle continues to accelerate and the motor back electromotive force continues to increase, requiring a higher voltage and a lower current to maintain constant power. Note that during span B the motor voltage is first below and then above the fuel cell voltage, requiring a controller with both step-down and step-up capabilities. At the beginning of span C the vehicle has reached its maximum speed and no further change in voltage, current, or power occurs. The present controller weighs 300 pounds, but a redesigned version that weighs 150 pounds will soon be installed.

The peak acceleration of the vehicle equipped with four fuel cell modules and a supplementary lead-acid battery pack is compared with that of a truck equipped with the standard 94-horsepower gasoline engine in Figure 7. With only 20 kilowatts of fuel cell capacity the truck readily climbed grades of 20 percent. The maximum speed on a good level road was 47 mph. Fuel consumption was between 10 and 15 miles per gallon of hydrazine menohydrate; that of a standard M-37 vehicle is 7 miles per gallon of gasoline. The reliability of the fuel cell has been good in the 120 hours it has been used.

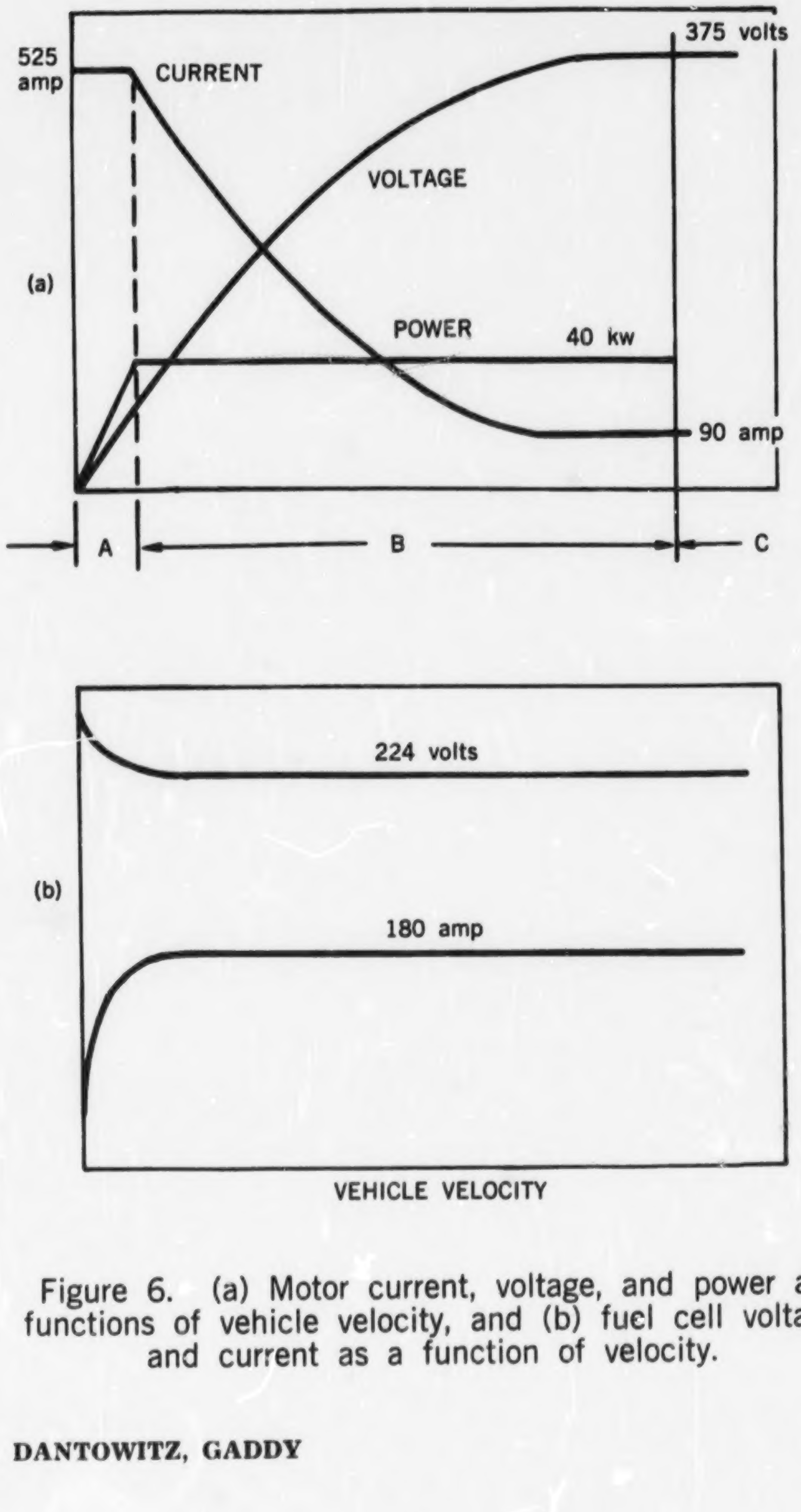

Figure 6. (a) Motor current, voltage, and power as functions of vehicle velocity, and (b) fuel cell voltage and current as a function of velocity.

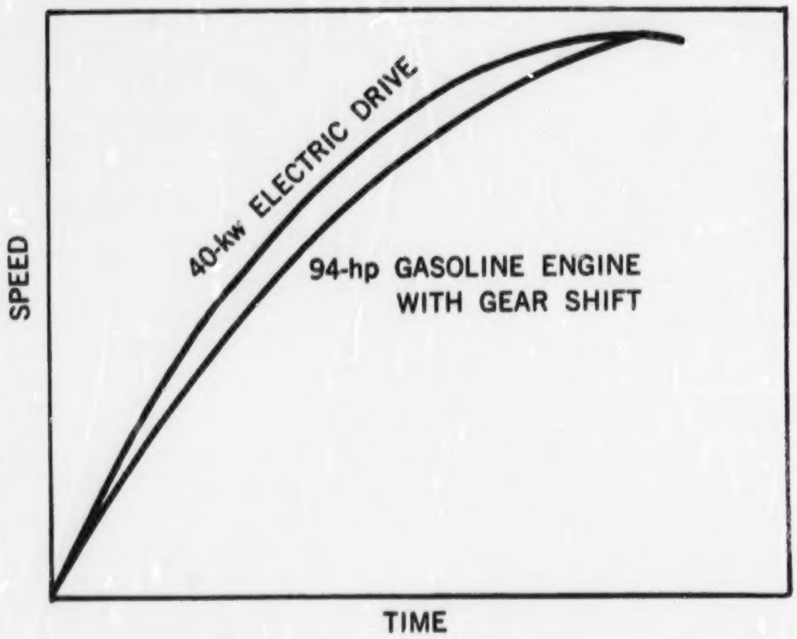

Figure 7. Comparison of acceleration of electric- and gasoline-powered M-37 truck.

SIGNIFICANCE OF THE PROJECT

As installed in the truck the hydrazine-air fuel cell system (excluding the motor and controller) gives a very high energy density, nearly 350 watt-hours per pound for an 18-hour mission. For an eight-hour mission the energy density drops to 210 watt-hours per pound, still much higher than is offered by any other readily available system. The successful operation of the M-37 truck with a system having such a high power density must be considered an important step forward in the practical application of fuel cells.

Using the hydrazine-air system, the Army has gained valuable experience in the operation and control characteristics of an electric vehicle. The relative simplicity and ease of operation of this large hydrazine-air fuel cell power plant has been demonstrated by over 100 operating hours in the truck.

FUTURE DEVELOPMENTS

We have seen that a start has been made in applying fuel cells to automotive use. To make further progress, research and development efforts must be continued and intensified. These programs have been split into short-range and long-range efforts for which successful completion is visualized in 2 and 5 years, respectively.

The highest priority short-range program is the minimization of the use of platinum in the electrodes. With two 5-kilowatt modules as they presently exist, and reasonable reclamation and capital costs for the platinum, annual expenditure of well over $500 is incurred by the use of precious metal. This figure probably must be reduced to around $100 per year for wide acceptance by the public. Monsanto has already demonstrated the feasibility of achieving such a light platinum loading. Much work remains to be done, however, to optimize the platinum loading and to reduce the resulting electrode to a practical, reliable, and durable component.

Improvement of reliability and durability of the fuel cell is second on the priority list. In concept the fuel cell promises to be highly reliable and very durable, matching and ultimately exceeding the lead-acid battery in these respects. Although the fuel cell of today has not lived up to this promise, in a relatively short time great improvements have been made. Most first-order failure mechanisms have been identified and eliminated so that 1,000 hours of life is common on a single cell. Since a practical fuel cell battery contains 30 or more cells in a series, the problem of battery life is more severe than that of a single cell. Consequently, much work needs to be done to identify second-order life-limiting phenomena and to find ways to extend life and reliability. A goal of 1,000 hours of stack life is reasonable for the short term, since it would give the average motorist 2 to 3 years of operation.

Third priority for the short term is reduction of specific weight. Engineering studies have shown that a 10-kilowatt fuel cell module weighing only 75 pounds can be developed in the short term. Although optimistic, this goal can be reached by the application of sound engineering principles in a disciplined design effort.

If all three of these goals are met, an attractive first-generation fuel-cell power plant will result. An annual market of 25,000 units of 10 kilowatts each could very well be captured by such a machine. A 2,000-pound vehicle so equipped would use about a pound of hydrazine for every 5 miles. If each vehicle traveled an average of 15,000 miles per year, the total annual consumption of hydrazine would be 75 million pounds per year at the end of the first year and 150 million pounds per year at the end of the second. Without a doubt, production rates this high would bring the price of hydrazine down. How far down is a matter of speculation, but it appears possible that with a high enough demand the price could be reduced to a level roughly competitive with gasoline prices. The retail hydrazine sales volume would be several million dollars a year, sizeable enough to warrant appreciable plant investment.

Because the early realization of all the goals just described is unlikely, only an extreme optimist would cite such a probability. The main point is, nevertheless, that the fuel-cell-powered vehicle, even for the short range, remains a possibility.

If the hydrazine industry does not meet the challenge of achieving a competitive price, a cheaper fuel will have to be found. Much of the work done on the hydrazine system will be applicable because the air cathode will still be used. A possible alternative to hydrazine is hydrogen obtained by on-board conversion of one of the following: saturated hydrocarbon, methanol, or ammonia.

In each case the annual cost of fuel for 15,000 miles of travel would be less than $300 (a 2,000-pound vehicle dissipating 160 watt-hours per mile at the wheels). Production of hydrogen by any of the three methods offers no scientific obstacle. That is, processes and materials such as catalysts are well defined and have been reduced to practice. It remains to engineer the best of them into a practical, lightweight hydrogen generator for use in an automobile. Logistic considerations allow only liquid saturated hydrocarbons to be considered for widespread military use.

In moderate quantities, production of fuel cells with minimized platinum loading could be easily sustained by present production of the precious metal. If the fuel cell is to replace the internal combustion engine to a significant degree, however, then a long-term goal must be elimination of the use of platinum-group metals in the fuel cell.

Finally, the ultimate objective of every fuel cell researcher is the direct oxidation of a low-cost liquid fuel. It has been demonstrated that under the proper circumstances saturated hydrocarbons can be electrochemically oxidized at appreciable rates. Thus far, however, this has been accomplished by using far more platinum (and other platinum-group metals) than can be tolerated for the application under discussion. Furthermore, the power density of the cells produced has been very low, and therefore power plants utilizing them would be expensive, heavy, and bulky. Research continues on direct oxidation of liquid saturated hydrocarbons to reduce the platinum loading and to increase the power density, and thus decrease the cost, weight, and size of the resulting power plant. Many are convinced that for nonmilitary use a more timely consummation of a practical fuel cell can be achieved by using a fuel that is more active electrochemically than the saturates. The two most important candidates are methanol and ammonia. These fuels are reasonably priced for automotive use; both are plentiful and can be readily stored and distributed.

It has been demonstrated that fuel cells for automotive use are a possibility. The chances for success depend upon the level of support the research and development effort gets. A vigorous and determined program could very well make the fuel cell automobile a reality in the 1970's.

DIRECT HYDROCARBON AND METHANOL-AIR FUEL CELLS

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M. Beltzer, and G. Ciprios
Esso Research and Engineering Company
Linden, N. J.

The fuel cell has been proposed as a potential solution to the problem of automotive exhaust emissions. Such a power plant would not be subject to the limited range of battery vehicles and would serve a broader spectrum of transportation needs. The specific requirements for an automotive fuel cell power plant have not been defined; however, as a first approximation a fuel-cell-powered vehicle should at least approach the performance capability of the conventional vehicle. For simple control, reliability, ease of start-up, and adaptability to a variety of driving conditions, system complexity should be avoided. Thus, direct fuel cells are preferred to indirect systems. Although high efficiency will reduce operating costs, this economic advantage would be quickly offset by a fuel cell that contains costly components and materials. A practical fuel cell power plant should use a readily handled, inexpensive fuel and air as the reactants. Finally, if the fuel cell is to provide a solution to exhaust emissions, the fuel cell reactions should yield inoffensive products; unconverted fuels and intermediates should be contained.

Fuel cell research at Esso Research, although primarily aimed at the development of military field generators, has identified some of the problems that must be solved before fuel cells can meet these requirements. This program includes work on direct liquid hydrocarbon and methanol-air fuel cells. Both fuels satisfy the requirement of a readily handled inexpensive fuel, but the higher cost per Btu of methanol places a greater premium on high efficiency than necessary for hydrocarbons.

Substantial progress has been made on the development of hydrocarbon fuel cells (Figure 1). Since 1959 when direct electrochemical oxidation of ethane was first demonstrated in our laboratories (Heath and Worsham, 1963), hydrocarbon fuel cell power density has been dramatically increased. A modified Bacon cell operating on ethane and oxygen sustained 1.5 watts per square foot at 400°F and 20 atmospheres. The voltage was 0.2 volt. In 1966, an octane-air fuel cell, operating at 525°F and atmospheric pressure generated 90 watts per square foot at 0.5 volt. The early porous electrode required a complex differential pressure control mechanism to maintain the fuel-electrolyte-electrode interface. Current electrodes, based on a catalyst-Teflon matrix, are not flooded and can be designed for either vapor or liquid reactants. Finally, the early work used a 30 percent KOH electrolyte, which obviously would not remain invariant. The present cells all use CO_2-rejecting acid electrolytes.

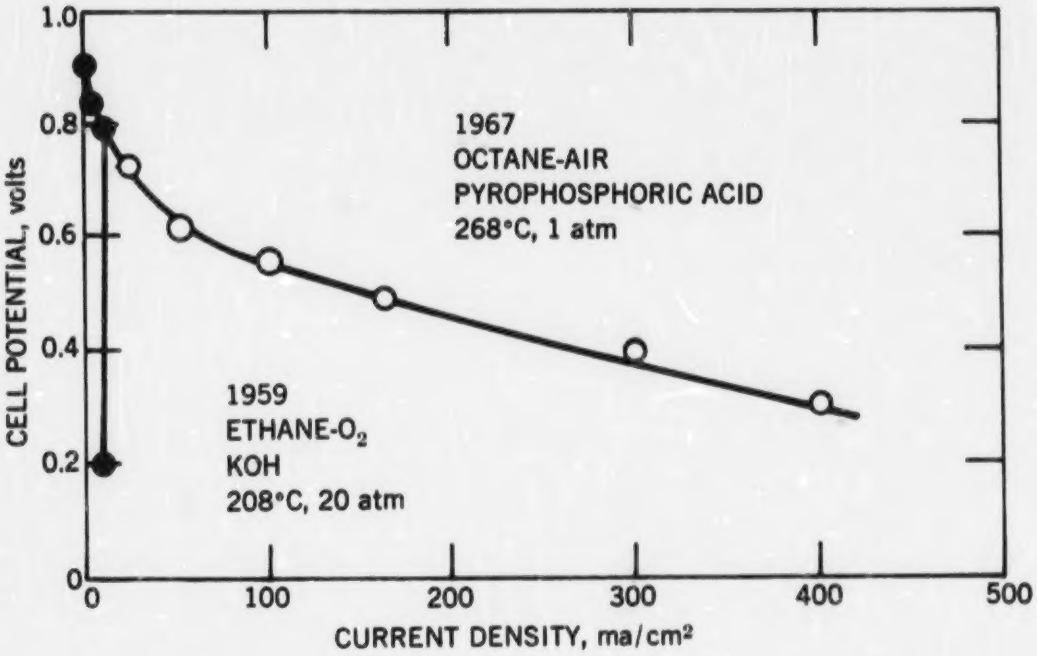

Figure 1. Progress in hydrocarbon fuel cells.

These performance levels have been achieved under conditions that ensure rapid electrochemical oxidation and high current densities — heavy catalyst loadings and temperatures of 500°F. The fuel electrode catalyst was platinum at 50 milligrams per square centimeter. The catalyst loading can be reduced by a carbon support, but at the expense of some performance. For example, a butane-air fuel cell with total catalyst loadings of 3.2 milligrams per square centimeter for both electrodes yielded 53 watts per square foot. The temperature was 525°F. Thus, catalyst utilization was increased from 0.7 to 17 milliwatts per milligram. Other supports have been investigated, but show no major advantage over carbon.

High power densities can be obtained only at temperatures above 300°F. Although phosphoric acid is suitable up to 300°F, new electrolytes are needed for higher temperatures. Two new electrolytes now under development make it possible to reach increased power levels. One, pyro-phosphoric acid, is similar to the aqueous systems investigated in the past and does not require special electrodes. However, it is highly corrosive and new materials are needed. The other, mixed alkali phosphates, is not corrosive, but because of its viscosity will require development of specific electrodes. The current performances of these and the conventional electrolytes are summarized in Table 1.

Table 1. HYDROCARBON FUEL CELL PERFORMANCE IN DIFFERENT ELECTROLYTES[a]

		Electrode polarization from theory,[b] v at 100 ma/cm^2	
Electrolyte	Temperature, °F	Butane	Oxygen
H_2SO_4	205	30 ma/cm^2 max.	0.35
H_3PO_4	300	0.35	0.30
Pyrophosphoric acid	480	0.18	0.08
Mixed alkali phosphates	480	0.27	0.18

[a] These data are based on runs of several hours. During prolonged operation electrode structure can deteriorate through thermal stressing.

[b] Platinum catalyst loading: 50 mg/cm^2 at each electrode, except O_2 in H_2SO_4 (20 mg/cm^2).

Obviously, a fuel cell power plant will consist of more than the basic module. The hydrogen-oxygen automotive fuel cell power plant recently demonstrated by General Motors contained 1,485 pounds of auxiliaries, almost twice the weight of the conventional engine (SAE, 1967). A decane-air battery system was developed and constructed in our laboratories to determine systems problems that must be faced in a direct hydrocarbon fuel cell battery (Okrent and Heath, 1967). This system included auxiliaries for water balance, fuel and air circulation, electrolyte concentration control, and other necessary functions. Although this system was not engineered as a prototype, this study confirmed that auxiliaries would represent a substantial portion of a practical power plant.

The study also indicated the problems that would be faced in using practical hydrocarbon fuels. The electrodes were designed for use with decane. Although equally effective for vapor and liquid phase fuel, the electrodes are sensitive to molecular weight. Low-molecular-weight hydrocarbons will diffuse through the structure into the electrolyte chamber. When a wide-boiling-range fuel is supplied, some light ends will cross to the cathode, give rise to a mixed potential, and reduce cell voltage. This effect was illustrated by experiments in a three-cell hydrocarbon battery in which decane, the research fuel, was replaced with a commercial jet fuel, OTF-90 (Supplied by Humble Oil and Refining Co.). This fuel is a low-sulfur isoparaffinic fuel with a boiling range of 195° to 290°C. As shown in Figure 2, performance declined to 30 percent of that of decane. Inspection of the cells indicated that the fuel had diffused through the anode.

Based on these studies, preliminary projections of complete hydrocarbon-air fuel cell power plants can be made. Projected weights can be compared with the weight of the total fuel cell power plant used in the General Motors Electrovan (Table 2). This power plant was rated at 21 pounds per kilowatt. The hydrocarbon-air fuel cell, if built with today's technology, would clearly exceed the weight and volume of the hydrogen-oxygen battery, which itself was excessively heavy. The noble metal catalysts alone preclude economical application of the direct hydrocarbon fuel cell as an automotive power plant. The search for active non-noble metal substitutes has been under way for 5 years. Many leads have been followed to extinction; new leads are being uncovered. The nature of catalyst research makes it impossible to predict when a suitable material will be found.

Methanol is considerably more active than hydrocarbons and might be considered for this application. Much progress has been made in improving this activity (Figure 3). Methanol fuel cells have yielded power densities as high as 50 watts per square foot at 160° to 190°F in short laboratory tests. However, it should be emphasized that deterioration occurs and further research will be required to maintain this performance. The low temperature activity would make the methanol cell easier to start than the hydrocarbon cell, but it is inadequate for an automotive power plant. Attempts to improve the power density significantly further by increasing cell temperature have been unsuccessful thus far, although the approach deserves more consideration.

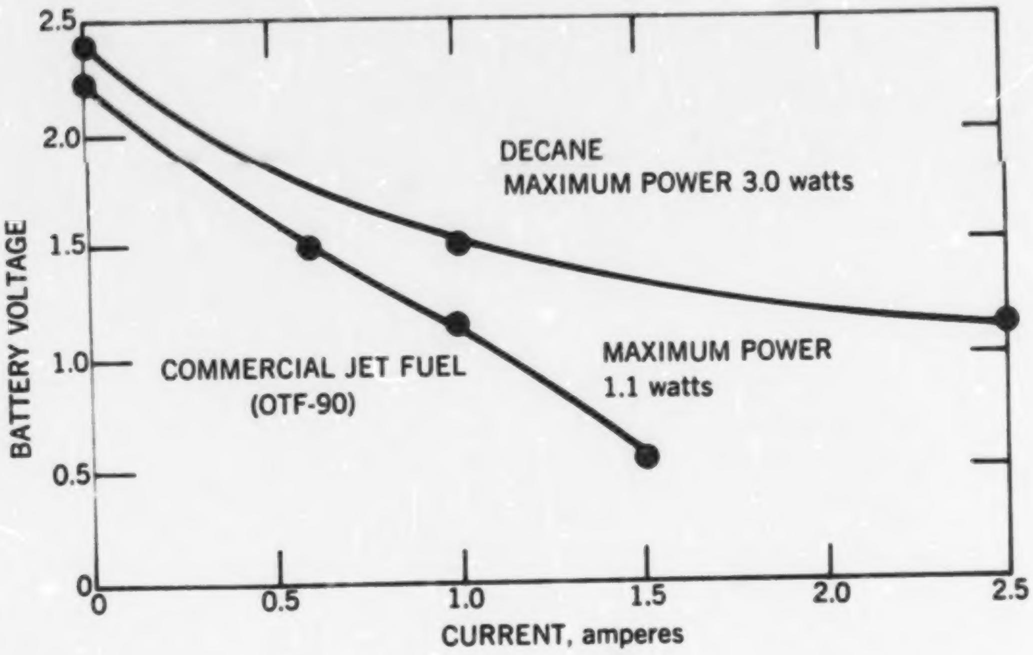

Figure 2. Wide-boiling-range fuels reduce fuel cell performance.

Table 2. COMPARISON OF WEIGHTS OF COMPLETE HYDROCARBON FUEL CELL SYSTEMS, ELECTROVAIR POWER PLANT, AND CONVENTIONAL ENGINES.

	System power density,[a] lb/kw	Catalyst quantity, g/kw
High-performance hydrocarbon fuel cell system[b]	50 to 70	1,600
Low catalyst loading hydrocarbon fuel cell system[b]	65 to 90	60
GM Electrovan power plant	21	—
Conventional engine	8 to 12	—

[a] Fuel cell power plant densities do not include electric drive. GM system drive weighed 3.4 lb/kw.

[b] Based on fuel cell size. Higher power densities are based on 5-kw design, lower on 30-kw systems.

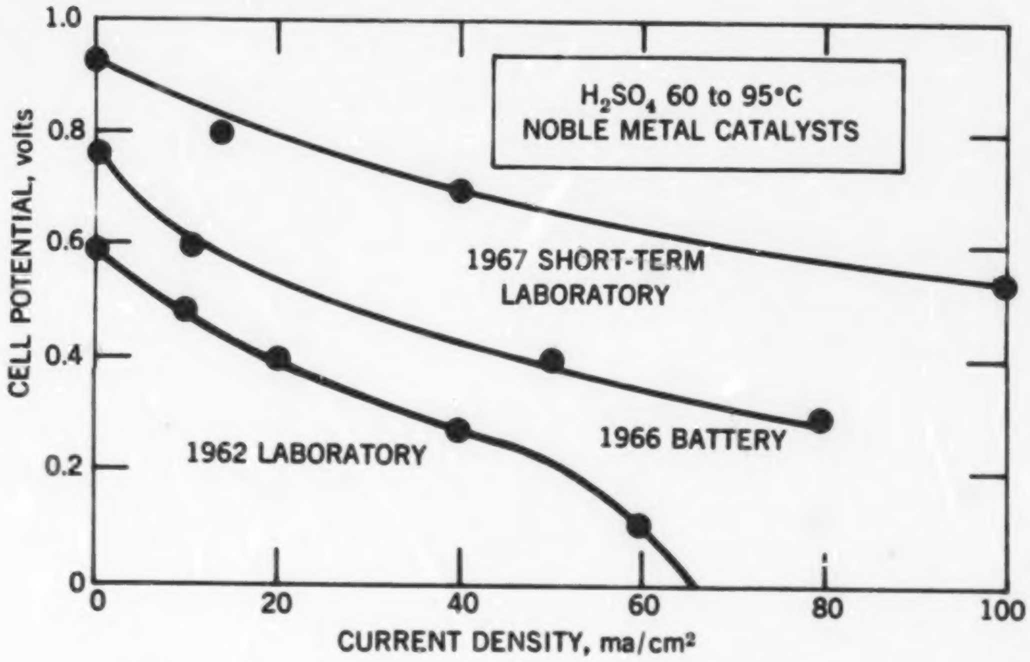

Figure 3. Methanol — air fuel cell improved but noble metal catalysts needed.

The question of whether the fuel cell can reduce air pollution cannot be conclusively answered yet. Direct hydrocarbon cells, operating at temperatures below 500°F, appear to offer no serious source of contamination. Studies have shown that hydrocarbons are completely consumed to carbon dioxide and water in sulfuric acid electrolytes at 90°C. Fuel cell fuels will probably be sulfur and lead-free.

Furthermore, the low temperatures should minimize nitrogen oxide formation. Hydrocarbon losses from manifolds and tanks may cause a problem, but using low vapor pressure fuels and proper engineering should minimize this contribution. No major obstacles to a low-emission vehicle are known, but clearly much more experience will be required to define pollution levels in operative systems.

From this discussion it is evident that the present state of hydrocarbon fuel cell technology cannot meet the requirements of a high-output, low-cost system suitable for extensive vehicular application. Much progress has been made during the past 5 years. If this progress continues and suitable catalysts are developed, a fuel-cell-powered vehicle could become practical. However, much more research and development will be needed before this stage is reached.

ACKNOWLEDGEMENT

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HYDROGEN-AIR FUEL CELLS FOR VEHICLE PROPULSION

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A very large variety of power sources have been proposed for the future electric vehicle. In broad terms they can be divided into two classes—rechargeable batteries and fuel cells. Rechargeable batteries include conventional types such as lead-acid, nickel-cadmium, and silver-zinc, and newcomers such as rechargeable metal-air, sodium-sulfur, and lithium-halogen types. Fuel cells include the well-known hydrogen-air types, direct or indirect hydrocarbon-air types, and a large variety of miscellaneous types burning hydrazine or other even less common fuels.

In general, rechargeable batteries are characterized by high power density (watts per pound) and low energy density (watt-hours per pound). The converse is true of most fuel cells; they offer high energy density, but usually at a sacrifice in power density. Since Union Carbide Corporation manufactures both rechargeable batteries and fuel cells, we can be impartial in judgment, and in fact, what we will propose is a hybrid system: a fuel cell with a very high energy density to provide long driving range and rapid refueling, and a rechargeable battery to supply peak loads.

When discussing a proposed power source, it is important to define and weigh the requirements, so as to avoid the danger of sacrificing life for low initial cost, or safety for power density. The following objectives or performance goals for a vehicular power supply have been used in arriving at the proposed system; not necessarily in order of importance:

1. High power density, e.g., at least 40 watts per pound;
2. High energy density, e.g., at least 40 watt-hours per pound.
3. Freedom from harmful emissions.
4. Low initial capital cost, rather arbitrarily set at a maximum of twice the price of an internal combustion engine vehicle.
5. Low fuel cost, comparable to the price of gasoline.
6. Low maintenance costs.
7. Long life—as a yardstick, the power plant should last at least as long as the body.
8. Safety; last but not least, the electric vehicle should provide greater safety on the road than the present gasoline vehicle.

A package consisting of a hydrogen-air fuel cell, using cryogenic hydrogen as fuel, and a rechargeable battery for peak power appears to be a leading contender for meeting these requirements in the near future. The operational characteristics of the hydrogen-air system make it more suitable for industrial or commercial vehicles—delivery trucks and vans, city buses, taxicabs, etc.—than for the private automobile. Thus, we visualize the hydrogen-air fuel cell as a practical power source for industrial and commercial fleets of vehicles within the near-term future, whereas improved rechargeable batteries may more readily meet the needs of lightweight electric vehicles for use as private automobiles under short-range, urban driving conditions.

In the following discussion, the present status and future potential of hydrogen-air fuel cells will be discussed in the light of the above eight objectives. It is important to remember that these eight objectives must be met simultaneously: there is little merit in a system that offers high power density at the risk of safety or long life at the expense of exorbitant cost.

CONCEPTUAL DESIGN

Many of the advantages of the hybrid hydrogen-air fuel cell can be made more explicit by considering an actual vehicular system. For this purpose we have started with the General Motors Electrovan as a baseline. The performance of this vehicle, as well as the detailed weight and volume breakdown of its components, has been fully documented in a series of papers presented to the SAE Automotive Engineering Congress this past January. As a short-term, state-of-art approach, we have simply looked at the problem of replacing the hydrogen-oxygen fuel cell of the Electrovan with a hydrogen-air fuel cell plus a rechargeable battery.

Based on Electrovan performance data, a hybrid fuel cell system has been sized to provide 32 kilowatts of continuous power and 160 kilowatts of peak power. A weight breakdown of the hybrid system is given in Table 1.

In SAE Paper No. 670176, Marks *et al.* (1967) mention that a "production model" Electrovan could weigh at least 1000 to 1500 pounds less than the prototype model, by elimination of experimental instrumentation and through normal engineering optimization. Any such weight savings are in addition to the gains shown in Table 1, which result from use of a different type power source. For example, Table 1 shows a weight of 164 pounds for the hydrogen supply, of which 128 pounds is the weight of the actual fuel tank aboard the Electrovan. As a conservative estimate, a fully optimized hydrogen fuel tank for this vehicle will weigh no more than 80 pounds.

Table 1. COMPARATIVE WEIGHTS OF ELECTROVAN AND FUEL CELL POWER PLANT COMPONENTS
(in pounds)

	Electrovan	Hybrid system—this study
Fuel cell stacks	1,345	690
Peak power battery	—	427
Fluid system	1,097	704
Fuel and fuel tankage	164	164
Oxygen and oxygen tankage	208	—
Electric system	569	380
Electric motor drive and controls	550	550
Power train total	3,933	2,915

The weight of the fuel cell stacks is reduced since the fuel cell is no longer required to handle heavy overloads; a hydrogen-air system designed to a 32-kilowatt rating without overload requirements is only about one half the weight and volume of a 32-kilowatt hydrogen-oxygen system designed to handle 160-kilowatt peak loads. Reduced fuel cell volume produces corresponding reductions in the weight and volume of interconnecting plumbing, tankage, etc. As a result, the 427 pounds added in a battery to handle peak loads is more than compensated for by reductions in fuel cell weight. Another significant weight reduction results from dispensing with a 208-pound liquid oxygen tank; only about one half of this weight need be added on in air processing equipment aboard the hydrogen-air system.

Table 2 lists the performance factors chosen for the Electrovan system. Simple replacement of the hydrogen-oxygen system of the Electrovan with the hybrid hydrogen-air system would give above-target performance, because of the lower power train weight. This permits design to a lower power level, or alternatively permits an increase in useful cargo weight.

Table 2. PERFORMANCE

Variable	Electrovan
Acceleration (0 to 60 mph), sec	30
Top speed, mph	70
Range, miles	100 to 150

Rather than attempting to redesign the Electrovan to a new set of weight figures, a simpler way is to interpret the data of Table 1. The Electrovan weighs 7,100 pounds. Table 1 shows that with a 3,933-pound power train, 55 percent of the total weight is required to give it the design performance of Table 2. With a hybrid hydrogen-air system, the same performance can be provided in a 7,100-pound gross weight vehicle with a power train weight of 2,915 pounds, or 41 percent of the total weight. In a recent article Hoffman (1966) indicated that up to 50 percent of the weight of an electrical vehicle could be assigned to batteries without endangering utility; by this criterion the Electrovan just misses, wherein the hybrid system is well within the safe range.

The data in Tables 1 and 2 are not intended to project long-range future goals, but rather to indicate what can be accomplished in the near future. Our longer-range projections are far more optimistic.

Many criteria other than weight and power are important in evaluating a power system. In the following discussion, the characteristics of the hybrid fuel cell system are weighed against the eight criteria previously listed.

High Power Density

Weights estimated for the fuel cell of the hybrid system are based on a peak electrode power density of about 75 watts per square foot at the 32-kilowatt design point. This represents performance that has been achieved already in smaller multicell hydrogen-air systems. This electrode power density represents a reasonable design goal for a number of nonnoble metal catalysts being investigated by us and in other laboratories. The trade-off between performance and cost leads directly to the hybrid system. The many kilowatts of peak power required for vehicle acceleration are most economically provided by a rechargeable battery, whereas the fuel cell provides instant refueling capability and high energy density needed for an acceptable range in miles.

The feasibility of the hybrid fuel cell and rechargeable battery combination was demonstrated a few months ago by Kordesch in a small motorcycle, using a hybrid power plant employing an 800-watt hydrazine-air fuel cell plus a set of nickel-cadmium 15-ampere-hour batteries. No electronic charge controls were necessary; a simple matching of the fuel cell and battery discharge characteristics provided proper load-sharing.

The rechargeable battery employed in the hydrogen-air design of this study has been characterized thus far only as weighing 427 pounds, and as being capable of delivering short bursts of power up to 128 kilowatts. Several of the rechargeable batteries presently being proposed as the sole power source for electric automobiles can meet or surpass this requirement; feasibility of the hybrid system does not depend upon inventing a new battery system.

High Energy Density

The hybrid system contains 120 kilowatt-hours of energy in the fuel tank. If we assume that storage batteries with an energy density of 50 watt-hours per pound become available for vehicle propulsion use, the rechargeable battery of the hybrid system can store an additional 21 kilowatt-hours for a weight of 427 pounds. Since the power train weight is 2,195 pounds (including motors and controls), this gives about 50 watt-hours per pound as the energy density of the total power supply, including fuel tank and motors.

The energy density of the fuel cell portion of the system is about 77 watt-hours per pound. If the fuel tank size were doubled, increasing the range from between 100 and 150 miles to between 200 and 300 miles, the fuel cell energy density would increase to about 140 watt-hours per pound, with an additional 140 pounds added to the system weight.

The use of the rechargeable battery for supplying peak power provides a useful fringe benefit; should the vehicle run out of hydrogen, the battery will give about 20 miles additional range to reach the next filling station.

Freedom from Harmful Emissions

The absence of noxious exhaust fumes is perhaps the most obvious and most easily sold advantage of hydrogen-oxygen or hydrogen-air fuel cells. The only possible reaction product, even in theory, is pure water. By-product water from Union Carbide fuel cells has been checked by the testing laboratory that monitors Cleveland's water supply and found to meet U.S. Public Health Service standards for potable water.

It might be argued, since we are proposing hydrogen-air systems and commercial hydrogen is produced largely by steam reforming of natural gas, that we are simply moving the source of pollution from the vehicle back to the hydrogen manufacturing plant. This is not a valid argument. A major hydrogen production plant can, and does, cut down emission of atmospheric pollutants to a negligible level, using techniques that are practical in a plant covering city blocks in area, but that would be totally impractical to apply to each of millions of individual vehicles. For example, even in the long-range future when fossil hydrocarbon fuels become unavailable or more expensive, the vehicle described in this study could be operated on hydrogen produced by electrolysis of water by use of nuclear electricity.

Low Capital Cost

The question of initial capital cost for a fuel cell installation has probably limited or at least confused the growth of the fuel cell industry more than any other item. Fuel cell prices today are quoted anywhere from about $15,000 per kilowatt, to well over $40,000 per kilowatt, depending upon type. A very large percentage of this cost is for labor. There is scarcely a component or part of the Union Carbide fuel cell system that can be purchased from a mass-production supplier; even such simple parts as pipe couplings may have to be hand-crafted one at a time from bar stock. Under these conditions, the only realistic gauge available for estimating potential future prices is the cost of the materials that must be used. Unfortunately, no studies have been conducted in sufficient detail to provide quantitative information. The following comments are intended merely to set some qualitative guidelines.

A fuel cell system may be visualized as a group of electrochemical cells plus a group of auxiliary components such as pumps, fans, and radiators. These auxiliaries can be made of low cost materials such as a variety of modern plastics or nickel-plated steel and in general are no more complex in design than the corresponding pumps, fans, radiators, etc., of the internal combustion engine. For simplicity, then, let us write off fuel cell auxiliaries as being comparable in cost to the corresponding type of equipment required to operate an internal combustion engine, and focus attention on the electrochemical cells, which represent the largest unknown in the cost picture.

The Union Carbide hydrogen-air fuel cell contains nickel, carbon, and a variety of plastics such as polysulfone, epoxies, polyolefins, and Teflon. Adding up all of the materials, less catalyst, required for the 32-kilowatt hydrogen-air fuel cell gives a raw materials cost of about $1,500, or $50 per kilowatt. This estimate is based on our present purchase prices for raw materials, purchased in lots of a few hundred pounds (or sometimes a few pounds) per order. There is reason to believe that a reduction in cost to one half this value could be achieved under mass-production conditions. This corresponds to a figure of about $1 per pound for a miscellaneous assortment of nickel, carbon, and plastics, which seems intuitively reasonable.

In my earlier discussion of power density, a conservative figure of 75 watts per square foot was selected as the peak power density for electrodes. This represents our judgment at Union Carbide as to the best power density achievable at the present state of the art without using precious metal catalysts, and for an acceptable lifetime. Fabrication of electrode stock is already on a continuous strip, semiautomatic basis; full conversion to a high-speed automated production line is simply a matter of the requisite production engineering and capital investment.

We have not discussed two other problem areas: the controls that regulate motor speed and the motors themselves. The approach used by General Motors in the Electrovan supplied a sophisticated, but rather expensive, solution to the problem. Not being manufacturers of traction motors or motor controls, Union Carbide will be pleased to hear of any practical and economic answers to these problems from specialists in the field. It is also obvious that any electric vehicle powered by a direct-current source will have to face and solve the same problems.

From this rather cloudy cost picture, it appears likely that a hybrid hydrogen-air fuel cell system will remain more expensive than a corresponding internal combustion engine within the next decade, perhaps by a factor of 1.5 to 2. A portion of this cost differential can be written off against operating cost, a portion against the advantages of silence, a portion against the necessity of air pollution control, and a portion against the greater safety of a hydrogen-fueled vehicle as compared with a corresponding gasoline-fueled vehicle.

Low Fuel Cost

One of the advantages of the liquid hydrogen fuel proposed for the hybrid system is its low cost. To establish a basis for comparison, 1 pound of hydrogen burned in a hydrogen-air fuel cell gives about the same performance as 1 gallon of gasoline burned in an internal combustion engine. In recent contracts, government agencies have purchased liquid hydrogen for prices in the range of 20 cents per pound. Projections indicate that full utilization of plant capacity with insured sales to fuel distributors could lower the cost to 10 cents per pound in large quantities. This corresponds to 10 cents per gallon of gasoline, or in other terms, about 1 cent per mile of travel for a 7,100-pound gross weight vehicle under urban, start-stop driving conditions. The above figures do not include road tax. I am sure the Government will find a way to tax hydrogen when it is used as a vehicular fuel, but the fuel cost will still be attractive.

Low Maintenance Cost

Predicting maintenance costs for a system that has not yet been built invokes more prophecy than science, but a few clearly defined maintenance requirements can be foreseen. Operation of an alkaline electrolyte fuel cell on air produces potassium carbonate from the carbon dioxide in the air. If raw, untreated air is fed directly into an alkaline fuel cell operating at high power density, the buildup of carbonate deposits on and in the cathodes can produce a detectable loss of voltage within a few days. In order to avoid this problem, we extract a majority of the carbon dioxide from the incoming air in a "CO_2 scrubber," with the bulk electrolyte itself used as the absorbent. Laboratory experiments with small, 100-watt hydrogen-air systems have shown that we can get about 500 hours of operation before it becomes necessary to discard the electrolyte, flush out the system with water, and refill with clean electrolyte. Since 500 hours of operation represents 15,000 miles of vehicle operation at an average of 30 mph, this does not represent an intolerable maintenance burden. A refill of KOH electrolyte for the present 32-kilowatt hybrid design would cost about $38 (less than ¼ cent per mile).

Long Life

The life of a fuel cell is highly sensitive to the conditions of use and the criteria for failure; i.e., how much degradation in performance can be tolerated before the system is declared inoperable? Under laboratory conditions, we have operated small fuel cell systems for over 50,000 hours of intermittent duty, or over 14,000 hours of continuous duty, in the latter case at a time-average power density comparable to that proposed here for the 32-kilowatt system. Objectively, it must be recognized that these are "best results"—those isolated results that indicate merely that a goal is attainable, and not that it has been routinely reached. Consideration of the series-reliability problem, the fact that one bad cell in a stack can limit its life, suggests several thousand hours of on-load time as a more reasonable indication of the state of the art. We realize that a few thousand hours of life is not enough to provide the foundation for large-scale use of hydrogen-air cells, and are working hard to bring the average of the distribution up to the level of those best results.

The hybrid power source system contains two electrochemical devices; a fuel cell and a rechargeable battery. Developing a suitable battery for the hybrid system is a much simpler task than developing a rechargeable battery for use as the sole power source in an electric vehicle. In the hybrid system, the battery is subjected to very shallow discharges, is slowly recharged, and unless the operator runs out of hydrogen fuel, is never called on for more than a small fraction of its ampere-hour capacity. Any conventional rechargeable battery available today shows long life under these use conditions, and we foresee no major problem in meeting the rechargeable battery requirements of the hybrid system.

Safety

One of the major advantages of a conversion from gasoline fuel to cryogenic hydrogen fuel will be a reduced fire hazard in the event of traffic accidents. Weights assigned to the cryogenic tankage in the hybrid system are based on the criterion that the fuel tankage must not rupture unless impact is so severe that there is no reasonable chance for survival of the human occupants of the vehicle. Under these circumstances, the major hazard of concern is the probability that any resulting fire will endanger nearby humans, vehicles, or structures. Upon rupture and ignition of a liquid hydrogen tank, the contents vaporize immediately, rising in a vertical column of nonluminous flame which vanishes within seconds. In contrast, rupture and ignition of a gasoline tank results in the flow of heavy gasoline vapor and liquid gasoline across the ground, acting as a spreading and persisting source of fire. Furthermore, the gasoline flame radiates far more infrared or heat energy (because of incandescent carbon particles in the flame), leading to ignition of nearby structures or personnel not directly within the flame. On the basis of numerous experiments conducted for the government, the deliberate ignition of large quantities of liquid hydrogen unquestionably produces far less fire damage than ignition of a comparable fuel value of gasoline.

Union Carbide has been engaged in fuel cell research for about 15 years now, proving in and testing hundreds of kilowatts of hydrogen-fueled fuel cells. In logging over 5 million test hours on fuel cells, we have had three small fires, each easily extinguished and without injury or hazard to personnel. More important, in each of these incidents the causative factor could be traced to the use of pure oxygen. In a pure oxygen atmosphere almost anything is flammable (and hydrogen in particular). We do not propose the use of cryogenic oxygen in the future hybrid fuel cell system for this reason (but also because the use of oxygen would approximately double the operating cost per mile).

It is also noteworthy that our 15-year record of handling large quantities of liquid and gaseous hydrogen without a hazardous accident has been accomplished without our having to invoke extreme safety measures that might be impractical to apply in commercial practice. For example, we do not smoke while transferring liquid hydrogen. Neither should a filling station attendant when he is transferring gasoline.

Another problem related to safety concerns the handling of boil-off from the cryogenic hydrogen tank while the vehicle is garaged. This problem is easily solved in the hybrid hydrogen-air fuel cell vehicle, especially for commercial fleet users such as delivery trucks, buses and taxicabs. Such vehicles see heavy service 5 to 7 days every week. Over night or weekends the boil-off gas is simply supplied to the fuel cell, providing the fuel energy required to restore the rechargeable battery to full charge and maintain it there on trickle charge. This answer is not as directly applicable to the personal automobile, whose owner may leave it garaged for a month's vacation.

As a further safety precaution, any garage in which fuel cell vehicles are stored should be ventilated, to avoid hazard in the event of fortuitous hydrogen leakage from a defective system. Adequate ventilation can readily be provided, indeed is often already available, in large commercial garages of the sort used to store fleets of buses, delivery service vans, taxis, etc., but is not usually available in garages for the personal automobile. This again suggests that the first application of fuel cell vehicles can be to commercial types.

SUMMARY OF ADVANTAGES

In comparison with the internal-combustion-powered vehicle, the hybrid hydrogen-air vehicle will produce no air pollution, will operate silently, will operate at a comparable fuel cost, and will provide similar acceleration, speed, and range.

In comparison with the rechargeable-battery-powered vehicle, the hybrid hydrogen-air vehicle will provide greater range (as a result of higher energy density) and will permit instant "recharge" by filling the fuel tank. This ability to refuel quickly is a very important advantage. The vehicle discussed in this paper requires 140 kilowatt-hours of stored energy to achieve the desired range. If, as it has been suggested, the battery electric vehicle is to be recharged in 15 to 30 minutes while parked, this would call for a 280- to 560-kilowatt, direct-current charging station; definitely not a job for an extension cord. Consideration of charging problems again suggests that the hybrid vehicle may offer competitive advantages in heavy-duty vehicles with high energy storage requirements, such as buses and trucks, whereas the battery-powered vehicle may be more competitive in lightweight personal cars.

In comparison with the vehicle powered by the "pure" fuel cell the hybrid system offers lower weight, lower cost, an energy reserve in case the vehicle runs out of fuel, and a means of utilizing hydrogen boil-off in a safe and effective manner.

SUMMARY OF PROBLEM AREAS

The following areas require investigation and development before a vehicle powered by the hybrid hydrogen-air fuel cell can become a reality:

1. Improvement in quality and uniformity of electrodes and fuel cell stacks to permit the consistent achievement of long life at a power density of at least 75 watts per square foot, without increasing cost.

2. Development of a low-cost rechargeable battery offering at least 50 watt-hours per pound and capable of at least short bursts of power at a 128-kilowatt rate.

3. Development of inexpensive, lightweight motors and motor controls. This problem is a common one for any type of electric vehicle. Both fuel cells and batteries can provide high voltage only by coupling a large number of cells in series. Any electrochemical power source can be made lighter, more compact, and more reliable by reducing the number of series elements to a minimum. Furthermore, the voltage across the cells of a battery or fuel cell remains "on," even after the power supply switch is turned off. At high voltages, this can present a serious hazard to personnel. Either of the above reasons provides a strong incentive to design motors and controls to the very lowest voltage consistent with a tolerable weight and cost.

4. The specific 32-kilowatt hybrid system discussed here has been presented as a conceptual design, with only a first-order approximation of weights and other characteristics. An actual engineering design study needs to be conducted in sufficient detail

to permit an accurate appraisal of system characteristics. In turn, this information will permit more meaningful intercomparisons between vehicles powered with a fuel cell, a battery, and an optimized hybrid combination.

5. Upon arriving at a design projecting desirable and competitive characteristics, one must build and test a prototype. No amount of paper studies can provide the engineering advances achieved during the building and testing of hardware.

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